Investigation of Lead-Based Paint Contamination in Residential Soils within Urban and Suburban Areas of Palmerston North City, New Zealand

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Abstract

This study investigated the concentration and distribution of lead in soil at residential properties across the city of Palmerston North, New Zealand. Samples were collected from the topsoil of 34 urban and suburban properties constructed between 1901 and 1982. Three properties were subsequently investigated in detail using a 2m grid and sampling at 0-10cm and 11-20cm depth. Samples were prepared using acid nitrate digestion as per USEPA method 3050B and total lead analysis was completed using MP-AES.

Soil lead concentrations were elevated above the background concentration of 46.6mg kg^{-1} in every property investigated. There was a strong negative relationship between soil lead concentration and distance from house. There was no correlation between lead concentration and traffic volumes/density at any of the properties. There was a strong positive relationship between soil lead concentration and property age. On average, lead decreased with depth and was below the residential limit of 210mg kg^{-1} at the 10-20cm depth in most cases with the exception of well-mixed garden soils. There was a strong relationship between construction type and soil lead concentration with weatherboard homes exhibiting significantly higher concentrations than brick or stucco clad homes of the same age. These relationships indicate a point source for lead in residential soils from the weathering of lead-based paint that has been deposited on the ground through paint degradation with time, and through the stripping and sanding of painted surfaces prior to re-painting.

An estimated 511,000 homes constructed prior to 1960 in New Zealand present a significant source of potentially lead-contaminated soils. Soil lead concentrations have been directly linked to blood lead levels and emerging evidence suggests that there is no safe blood lead level, especially in children. The assessment and management of lead impacted residential soils presents a challenge for property owners, the contaminated land sector and regulators. The protection of human and environmental health is the driver behind contaminated land management and the current framework does not effectively address residential sources of pollution that may have cumulative impacts far greater than industrial source pollution.

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This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named above are responsible for the ethical conduct of this research. If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Prof Craig Johnson, Director, Research Ethics, telephone 06 356 9099 x 85271, email humanethics@massey.ac.nz.

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1.0 Preface

Anthropogenic impacts on the natural environment from past and present activities are the dominant cause of land contamination and have the potential to negatively impact human populations. Although the impacts of contaminants on human health has been acknowledged as far back as the classical period, it is only in the last 30-40 years that substantial efforts have been made to reduce population exposure to contaminated land. Contaminated land research and remediation has focused predominantly on the impacts of our industrial activities and the significant gross contamination that this has caused. More regulation has come with greater understanding of the impacts of industrial activities on the environment, allowing us to manage the risks of these activities better than they were just a few decades ago. The focus on industrial pollution has meant that activities on residential properties with the potential to contaminate land have generally been overlooked. The use of lead-based paint on residential properties does not initially appear to have the same magnitude of impact on the environment as an industrial source, until the prevalence of lead-based paint use is taken into account. The cumulative impacts of individual activities have the potential to impact large tracts of urban and suburban soils. The exposure risk from residential activities cannot be managed by the current New Zealand regulatory regime as the current framework focusses predominantly on industrial/horticultural source contamination. The research in this thesis aims to investigate the extent of lead contamination within residential soils as a result of historical lead-based paint use by focusing on the lateral and vertical distribution of lead across residential properties as well as investigating the variation of lead soil concentrations between dwellings of different ages and construction types in a regional New Zealand city.

2.0 Literature Review

2.1 Introduction

This literature review will introduce the topic of lead in the environment including the characteristics and behaviour of lead in soil and the various compounds the metal is a component of. The sources of environmental lead, both natural and anthropogenic, will be discussed with particular focus of lead-based products such as paints. A conceptual site model will be presented of common sources, pathways and receptors related to human and environmental lead exposure. The impacts of human lead exposure and neurological effects will be explored. Finally, the current regulatory framework for the management of lead in products, lead contamination of soil, and human blood lead concentrations, will be discussed using international and New Zealand examples. The next sections will summarise the previous work that has been done and introduce more recent work that is ongoing. Gaps in knowledge or research fields that have only been lightly explored will be highlighted and discussed in the context of the current research. An outline of this current research will then be presented including the purpose of the study and hypotheses for investigation.

2.2 Lead in the Environment

2.2.1 Lead and Soil Properties

The urban soil environment has been significantly altered by human populations almost everywhere in the world (Fergusson, 1986; Golder Associates, 2012). The most significant changes in terms of the impact on the environment have occurred with the industrial revolution, the advent of mass production, and technological and chemical advances (Fergusson, 1986). Lead has been used by human populations in Egyptian, Roman and Greek civilisations for more than 7500 years and its toxicological effects were recognised in these earlier times (Fergusson, 1986). Lead is a naturally occurring heavy metal that exists most commonly as oxides and carbonates (Yong et al, 2012). Lead in soil is derived from parent material and concentrations fluctuate across soils as a function of weathering and local geochemical processes (Fergusson, 1986). Trace elements such as lead are present in many different chemical forms in the soil environment (Clarke et al, 2015; Khan, 2013). Lead is not usually present in its elemental state, instead forming compounds including lead carbonates, acetates, oxides, arsenates, nitrates, sulphides, phosphates and chromates which are utilised for many industrial applications (Agency for Toxic Substances and Disease Registry, 2019; Clarke et al, 2015; Yong et al, 2012). The ratio between the different common lead compounds is strongly influenced by other soil properties such as iron and calcium content, humic materials, clay content and parent material (Khan, 2013; Ministry for the Environment, 2016; Yong et al, 2012). Soil pH plays the most significant role in lead mobility and the formation and ratio of lead and lead containing compounds in the soil environment (Clarke et al, 2015). Lead is generally immobile within the soil environment and does not leach except in extreme pH environments that would not typically be associated with residential urban areas that are the focus of the current study (Yan et al, 2015). Lead is amphoteric, reacting in both acidic and basic solutions, so a low pH or high chloride content (high pH) within the soil or water can increase lead solubility; depending on the compound it is present as (Agency for Toxic Substances and Disease

Registry, 2019). Despite the inherently low mobility of lead compounds within the soil environment, the tendency of the metal to sorb to fine particles allows for lead to be transported throughout the environment in suspension as dust or within ground and surface water (Agency for Toxic Substances and Disease Registry, 2019). Lead behaves differently depending on its form in the environment and the ratio of lead compounds can be important when interpreting the risk posed by lead soil concentrations (Yan et al, 2015). Soil lead compounds can be broadly categorised based on their chemical behaviour into exchangeable, reducible, oxidizable and residual fractions (Clarke et al, 2015; Yong et al, 2012). Exchangeable fractions of lead are bound to soil particles and move with sediment through the environment; they are readily bioavailable and are considered the most mobile form of lead in the soil environment (Agency for Toxic Substances and Disease Registry, 2019; Yong et al, 2012). Oxidizable fractions include lead that is bound to organic matter through adsorption or chelation (Yong et al, 2012). Reducible compounds such as lead carbonate are the next most bioavailable fraction and are significantly influenced by the pH of the environment which if acidic enough can break the ionic bonds within the compounds allowing lead to move more freely in an exchangeable fraction (Clarke et al, 2015; Yong et al, 2012). The residual fraction is the most closely correlated with natural background levels. Residual lead is a mineral form of lead often contained within silicate matrices and is the least mobile and least bioavailable fraction (Clarke et al, 2015; Yong et al, 2012). Lead is naturally found in soils within the reducible and residual fractions from weathering and erosion of parent rock material (Clarke et al, 2015). Organic content of soil can significantly influence the mobility of lead in soil (Yong et al, 2012).

Lead preferentially binds with organic material to form insoluble organic compounds in neutral pH environments between pH 6 and 8 (Agency for Toxic Substances and Disease Registry, 2019). Sequential extraction tests can be used to determine the ratio of soil lead in the reducible, residual, oxidizable and exchangeable fractions (Yan et al, 2015). Lead has been shown to preferentially adsorb to finer particles within a soil matrix, smaller soil particles also have a greater surface to volume ratio leading to a higher concentration of lead within the finer particle fractions (Ministry for the Environment, 2016).

2.2.2 Sources of Lead in the Environment

The dominant focus of investigations into lead contamination in the twentieth century was on point source pollution from heavy industrial activities such as metal smelting and battery manufacturing (Fergusson, 1986; Yan et al, 2015). Towards the end of the twentieth century, studies focused more on diffuse sources of lead such as particulate emissions from leaded petrol, resuspension of roadside dust, and past use of pesticides (Clarke et al, 2015; Laidlaw and Filippelli, 2008; Paltseva et al, 2018). More recent studies have examined other sources of lead in the environment such as lead-based paint (Clark & Knudsen, 2014; Clarke et al, 2015; Codling, 2013; Kandic et al, 2019; Rouillon et al, 2017; Tuner and Lewis, 2018; United States Environmental Protection Agency, 1995).

2.2.2.1 Naturally Occurring Lead

Background levels of trace elements are often difficult to define as measurements of soil concentrations have historically taken place after decades or centuries of anthropogenic change to the environment. Soil lead concentrations have been shown to be elevated above background concentrations in residential soils in many countries throughout the world, including in New Zealand (Smith et al, 2011; Seyefardalan et al, 2017; Turnbull et al, 2019). Within New Zealand, published background lead levels in soils range from 10mg kg^{-1} to over 200mg kg^{-1} in more urbanised areas, typically averaging 15-20mg kg^{-1} (Agency for Toxic Substances and Disease Registry, 2019; Landcare Research, 2015). Landcare Research (2015) undertook an extensive review of available background data as part of a project for Regional Councils within New Zealand. This research provided a comprehensive database of background soil concentrations for priority contaminants such as lead and arsenic across New Zealand that was estimated to predict surface concentrations based on parent material and geochemical processes, and correlated with localised data (Landcare Research, 2015). A concentration of 25.83mg kg^{-1} has been defined as the background surface soil lead concentration within all depositional areas around Palmerston North City including the main residential areas that are the focus of this current study (Landcare Research, 2015). Background concentrations are higher in erosional environments such as river the terraces at 46mg kg^{-1} because of the proximity to parent material of a higher concentration than is present in the depositional basin (Landcare Research, 2015). Given the agricultural and industrial history of Palmerston North City it is expected that the background concentrations of trace elements such as lead will be elevated above background concentrations.

2.2.2.2 Anthropogenic Sources of Lead

"Economic and industrial development since the mid-1800s has left New Zealand with a legacy of contaminated land" (Ministry for the Environment, 2016). Land that has been contaminated by polluting, historical activities range from industrial gasworks and timber treatment sites, agricultural contamination at sheep dips sites, orchards, to residential contamination from lead-based paint and leaded fuels (Ministry for the Environment, 2016; Paltseva et al, 2018; Seyefardalan et al, 2017). Lead is a common element present in many polluting activities and has been identified as a contaminant of concern in New Zealand and overseas contaminated-land regulation (Ministry for the Environment, 2011a; State of Queensland (Queensland Health), 2018). Lead is used for many industrial and commercial applications because of its versatility and durability, including battery manufacturing, construction, chemicals production, glass and paint manufacturing, plumbing and in fuels (Agency for Toxic Substances and Disease Registry, 2019). Eighty eight percent of all lead consumption in the USA in 2014 was by the lead acid battery industry. Lead from previously common industry uses such as agrichemicals, fuel additives and paint additives at the time of this report had been progressively regulated out of products where exposure had been shown to be significant (Agency for Toxic Substances and Disease Registry, 2019). Anthropogenic sources of lead fall generally into point source or diffuse source categories based on the mode of dispersal and temporal and spatial impact from contaminating activities. Point source polluting activities are characterised by high contaminant concentrations from an often readily identifiable source that impacts a defined area such as in the case of a gas works where hydrocarbon impacts are significant but often localised to the area of activity (Ministry for the Environment, 2011a). Point source pollution events often exhibit the greatest impact and are readily cited to explain chronic and acute symptoms recorded in exposed human and ecological populations (Yan et al, 2019). Heavy industries such as battery manufacturing and lead smelting have been some of the biggest contributors to environmental lead pollution (Francek et al, 1994; Freeman, 2012; Yan et al, 2015). Lead was also used in the textile, printing, ceramics and firearms industries, although with the exception of firearms it has largely been removed from modern practices (Agency for Toxic Substances and Disease Registry, 2019). Lead shot from testing ranges and firing ranges is another modern source of elevated environmental lead concentrations in small localised areas around the world (Clarke et al, 2015).

Diffuse pollution is more difficult to delineate and can involve multiple sources, pathways and areas of exposure. Diffuse pollution of lead has predominantly been through the use of lead additives in fuels, lead-based agrichemicals and lead-based paint, leading to significant emissions of lead into the environment, impacting large tracts of urban land (Fergusson, 1986; Jordan & Hogan, 1975; Paltseva et al, 2018). Lead was widely used in agricultural chemicals for pesticide and herbicide applications due to its toxicological properties (Paltseva et al, 2018; Rouillon et al, 2017). Pesticides such as lead arsenate were used extensively in commercial orchards for pest control but were also used in the residential environment by property owners (Paltseva et al, 2018). Both spills and regular application of lead-based agrichemicals can create hotspots of elevated soil lead concentrations around residential properties similar to that caused in commercial applications (Golder Associates, 2012; Paltseva et al, 2018; Seyefardalan et al, 2017). A study by local government in Christchurch, New Zealand in 1975 found that there was significantly elevated soil lead at residential properties from petrol additives and lead-based paint sources (Jordan & Hogan, 1975). A recent study in Christchurch, New Zealand, by Seyefardalan et al (2017) showed that residential soil lead concentrations can be higher than in industrial settings as there are fewer regulations regarding the residential application and use of chemicals. Prior to its removal in the late 1990's, lead additives in petrol were the largest contributor of environmental lead in major urban centres (Fergusson, 1986; Laidlaw and Filippelli, 2008; Lal & Stewart, 2018). Laidlaw and Filippelli (2008) showed that previously deposited lead in roadside soils was dispersed via resuspension in traffic flows and certain weather conditions, indicating that although lead has now been removed from fuels it has left a legacy that may impact human population for many decades to come.

Literature shows a pattern of research since the impact of lead exposure was 'rediscovered' in the 20th Century (Fergusson, 1986). Initially, investigations into industrial point source pollution from lead mines and smelters dominated the literature (Yan et al, 2015). Then as the impacts of lead additives in fuel became better understood the focus shifted to characterising the nature of contamination and exposure from leaded fuels (Jordan & Hogan, 1975; Fergusson, 1986). Finally, with the removal of lead from fuels in the 1990s, the focus of research shifted again towards other sources of lead with lead-based paint being the next focus for investigation (United States Environmental Protection Agency, 1995; Jacobs et al, 2002). However, this renewed interest in lead-based paint exposure may be a resurrection of the work that resulted in the regulation of lead in paints in the 1940's (Jordan & Hogan, 1975). This latest research into lead-based paint contamination over the last decade is driven by health research indicating that even low soil lead concentrations can result in elevated blood lead levels in exposed persons

(Ministry of Health, 2012; Nigg et al, 2008). A summary of previous research into lead-based paint contamination of soil is presented in Table 2.1 detailing the scope of the selected study and the headline findings.

In Palmerston North City the dominant contributor to soil lead concentrations is likely to be historical use of lead-based paint, lead containing pesticides on agricultural and residential land, and leaded petrol. Heavier industries found in larger urban centres overseas are not present within smaller cities such as Palmerston North and previous studies have shown that there is limited impact from these sources in a similar small urban setting (Clark & Knudsen, 2014). The land use histories of the properties included in the current study will help to determine the source of the any environmental lead. Lead-based paint as a source for lead in the urban and suburban residential environment is discussed in detail in the following section.

Table 2.1 Summary of studies investigating lead based paint contamination in residential soils since 1975.

Country	Year	Sample Location	N	Average mg kg^{-1}	Range mg kg^{-1}	Guideline Value mg kg^{-1}	% Exceed Guideline Value	Reference
New Zealand	1975	Gardens, lawns, entrances	437	NA	10-15500	300	38%	(Jordan & Hogan, 1975)
New Zealand	1992	House dust	120	724	12-3510	NA	NA	(Kim and Fergusson, 1992)
United States	1992	Playground soils	42	53	0-594	400	2%	(Francek et al, 1992)
United States	1995	Entrance, drip line, backyard	1053	74, 85, 46	1.16-22974	400	23%	(U.S. Environmental Protection Agency, 1995)
United States	2002	Playground soils	375	NA	NA	400	5%	(Jacobs et al, 2002)
United States	2013	Dripline and yard	237	NA	187-4796	400	100%	(Codling, 2013)
United States	2014	Dripline, yard, Road verge	170	NA	47-32483	400	66%	(Clark and Knudsen, 2014)
United States	2015	Vegetable Gardens	137	NA	18-1720	400	NA	(Clarke et al, 2015)
Australia	2017	front yard, dripline, back yard, vegetable garden	5200	413, 707, 226, 301	14-6490	300	40%	(Rouillon et al, 2017)
New Zealand	2017	Vegetable Gardens	65	282	7.96-2615	210	46%	(Seyefardalan et al, 2017)
Australia	2018	Vegetable Gardens	395	204	4-3341	300	21%	(Laidlaw et al, 2018)
United Kingdom	2018	Public spaces	21	48.3-27200	NA	450	100%	(Turner and Lewis, 2018)
Australia	2019	Vegetable gardens	108	102	12.9-773	300	13%	(Kandic et al, 2019)
New Zealand	**2019**	**Dripline and yard area**		**650**	**11.5-3644**	**210**	**47%**	**The current study**

2.2.2.3 Lead-Based Paint

Lead is commonly present in the environment and relatively easy to extract through mining. It has a low melting point, high malleability and a better resistance to corrosion compared to other metals (Fergusson, 1986). These attributes have historically made lead an attractive and effective additive for paints especially, but also fuels such as leaded petrol as it can provide benefits such as smoother acceleration (Fergusson (1986). Lead has historically been used in paints for commercial, industrial and residential purposes (O'Connor et al, 2018). Lead minerals and compounds such as lead oxides, lead chromates and lead carbonates were added to improve the flexibility, durability and finish of paints including pigmentation (Clark & Knudsen, 2014; Ministry of Health, 2012). The ability of lead to provide a thin yet durable and flexible surface when added to paints increased its appeal, especially in the form of lead carbonates and lead oxides, commonly referred to as 'white lead' and 'red lead' respectively (Fergusson, 1986). Paint with lead carbonate additives commonly known as white lead was the dominant exterior house paint used in domestic residential properties prior to its regulation in 1945 (Ministry of Health, 2012). In homes painted prior to 1945, the paint used was not regulated for lead and was more likely than not to contain high levels, often up to 50% by weight (Ministry of Health, 2012). The concentration of white lead was increasingly regulated in New Zealand from 1945 and was completely banned from paints intended for domestic use by 1965 (Jordan & Hogan, 1975; Ministry of Health, 2012). Homes first constructed before 1945 may have been heavily influenced by the higher lead concentrations in 'white lead' paints. Lead chromates were added into paint to provide a shiny and durable finish and were one of the last lead-based additives to be regulated out of paints in New Zealand, remaining in use well into the 1980’s (Ministry of Health, 2012). Red lead was commonly used in industrial or commercial settings as well and was used as a steel primer up until the 1980’s (Ministry of Health, 2012). It is feasible that lead-based paint would have been available domestically in the early 1980’s and domestic stockpiles may have still been in use into the 1990’s due to peoples tendency to store and utilise paint rather than disposing of it, or alternatively from large commercial purchases (Ministry of Health, 2012). Although efforts to reduce lead, specifically in domestic products and paints, have been largely successful in western countries, developing nations remain large consumers of lead-based paint (O’Connor et al, 2018). Lead-based paint in good condition does not in itself present a risk to human health, it is only when damaged that exposure becomes possible (Ministry of Health, 2012). The removal of lead-based paint during renovation, or flaking from deterioration, increases soil lead concentrations in the soils below (Ministry of Health, 2012; Turner & Lewis, 2018). Depending on the groundcover present, flakes of lead based paint can settle directly into the soil, or be dispersed by plants, grass and soil disturbance activities such as gardening (Paltseva et al, 2019; Turner & Lewis, 2018).

Initial research into lead-based paint contamination was small scale, in communities where lead exposure could not be entirely attributed to industrial sources of lead (Francek et al, 1992; Jordan and Hogan, 1975; Kim and Fergusson, 1992). The earliest study from New Zealand was carried out in Christchurch by the then Department of Scientific and Industrial Research which was a precursor to today’s local government bodies (Jordan & Hogan, 1975). The study was initiated following a case of lead poisoning in children that could not be attributed to toys or interior paints (Jordan & Hogan, 1975). Jordan & Hogan investigated soil lead concentrations and found concentrations in excess of the then SGV of 300 mg kg^{-1}, prompting further investigation of 437 properties across Christchurch (Jordan & Hogan, 1975). They showed a significant impact from both leaded petrol and lead-based fuels in weatherboard homes built before 1950 with concentrations of lead decreasing with depth and distance from the home and increasing with property age (Jordan & Hogan, 1975). The study by Jordan and Hogan (1975) also showed that weatherboard homes had significantly higher soil lead concentrations than all other construction types. The evidence presented by these studies was enough to draw the regulatory focus of the United States Environmental Protection Agency, who in 1995 undertook sampling of a nationwide subset of homes intended to represent the nation's housing stock (United States Environmental Protection Agency, 1995). The 1995 survey and analytical reports produced using the information gathered from more than 1000 residential soils samples predicted that 23% of the nation's housing stock built before 1980 would exhibit soil lead concentrations in excess of the national guideline value of 400mg kg^{-1} (United States Environmental Protection Agency, 1996). Jacobs et al (2002) repeated a similar nationwide study gathering 375 soil samples specifically looking into the soil concentrations within children's outdoor play areas. Jacobs et al (2002) reported that only 5% of playground soils exceeded the guideline value of 400mg kg^{-1} putting the relative risk in perspective. The majority of studies following on from the national survey investigated the risks posed by the high soil lead concentrations in terms of bioaccessibility (Ruby et al, 1996), particle grain size analysis (Smith et al, 2011), and the influence of soil properties on residential lead exposure scenarios (Oomen et al, 2006).

The majority of initial research on lead-based paint extent occurred in the 1990's in the United States with limited work completed elsewhere in the world.

More recent studies during the last decade have drawn the focus back to lead-based paint as a source of residential lead and a major factor in human lead exposure cases (Clark & Knudsen, 2014). Clark and Knudsen (2014) were the first and remain one of the few studies investigating smaller population centres instead of larger urban areas such as Los Angeles (Clarke et al, 2015). They found that in smaller population centres where industry and traffic density were less or absent that the dominant source of lead in residential soils was from lead-based paint where as in larger urban areas lead additives in fuels have been play a more significant role in residential lead concentrations (Clark & Knudsen, 2014; Clarke et al, 2015). Importantly they showed that 66% of the 171 soil samples gathered from predominantly older weatherboard homes were in exceedance of the guideline value of 400mg kg^{-1} and values as high as 32,000 mg kg^{-1} were found (Clark & Knudsen, 2014). However, recent research by Turnbull et al (2019) used isotopic analysis to show that there is some influence of leaded petrol on urban soils within Dunedin, New Zealand. A similar impact from leaded petrol on urban soils was found by Jordan & Hogan (1975) with soil lead concentrations taken from roadside soils elevated above background concentrations and as high as 200 mg kg^{-1}. It has also been demonstrated that lead-based paint contamination is characterised by a bullseye lateral distribution pattern around painted structures (Clark & Knudsen, 2014; Codling, 2013; Jordan & Hogan, 1975). This bullseye pattern is also seen in the distribution of lead concentrations across major urban centres, higher in the centre and decreasing outwards (Laidlaw et al, 2018). Most recently a contaminated land research initiative in Australia called VegeSafe has been operating since 2014 (Rouillon et al, 2017). The program allows home owners to sample and send in up to five soil samples from their property for XRF analysis by the program. This program has provided more than 5200 data points from major urban centres in Australia, like Sydney and Melbourne, as well as rural towns. The sheer volume of data provides a high level analysis of trends and relationships which are difficult to dismiss with concerns about sample integrity (Kandic et al, 2019; Rouillon et al, 2017; Seyefardalan et al, 2017). Another study to note is that carried out by Turner and Lewis (2018) in Plymouth, United Kingdom. They investigated the impact of lead-based paint on publicly accessible and permanent structures such as telephone booths, hand rails, bridge parapets and roads (painted) (Turner & Lewis, 2018). Their study found that lead is present in adjacent soils at elevated concentrations up to 260 times that of background concentrations near structures painted in lead-based paint (Turner & Lewis, 2018). Turner and Lewis (2018) contacted local authorities and owners of structures where elevated soil lead concentrations were found (British Telecom and Plymouth Council) who remediated around the study locations but did not show any willingness to investigate the pattern across their networks of thousands of similar structures. This unwillingness to investigate the wider trend is reflected in the lack of specific regulatory measures to protect human health in the residential lead scenario (Ministry for the Environment, 2011a; Turner & Lewis, 2018).

2.2.3 Housing Stock

Jacobs et al (2002) estimated that 38 million homes in the United States of America (USA) still had lead-based paint present either on internal or external surfaces. Properties constructed or painted prior to 1940 have been shown to exhibit the highest likelihood of lead-based paint (Jacobs et al, 2002; United States Environmental Protection Agency, 1995). Studies have shown that there is a limited risk of properties constructed after 1980 to be painted in lead-based paint (Jacobs et al, 2002; United States Environmental Protection Agency, 1995). The United States Environmental Protection Agency (2019b) estimates that lead-based paint may be present as a hazard in homes constructed or painted prior to 1978. This is estimated to be 68 million properties across the USA (United States Environmental Protection Agency, 2019b), nearly double that predicted by Jacobs et al (2002). The older the home, the more likely there is to be lead based paint, with homes built before 1940 having a likelihood of 87%, for homes built between 1940 and 1959having a likelihood of 69% for, and for homes built between 1960 and 1977 a likelihood of 24% (United States Environmental Protection Agency, 2019b). Using statistics New Zealand (2013) census data, we can show that in Palmerston North City there are estimated to be a total of 31,908 dwellings with 29,892 of those occupied. Of the 29,892 occupied dwellings, 23,487 were designated as separate standalone dwellings (Statistics New Zealand, 2013). These separate dwellings are the most common dwelling type in New Zealand and are the focus of this research. Page and Fung (2008) summarised available housing data sets in New Zealand to produce figures for the total number of homes categorised by decade of construction (this was current when produced in 2006). It is not anticipated that a large enough proportion of older properties would have been demolished in the 13 years following this estimate to significantly alter the housing stock in the older age bracket. Their analysis of the available data is adapted in Table 2.2 below and has been applied to the Palmerston North City 2013 census housing data to estimate the age distribution of dwellings in Palmerston North City. More recent census data did not include housing statistics so the census data from 2013 has been used (Statistics New Zealand, 2013).

Table 2.2 Age range distribution of New Zealand and Palmerston North City housing stock. Adapted from Page, I. and Fung, J. 2008. *Housing typologies –Current Stock Prevalence*. Report number EN6570/8 for Beacon Pathway Limited.

	New Zealand Distribution		Palmerston North City Distribution	
House Age	**Number of Dwellings**	**Percentage of Stock**	**Number of Dwellings**	**Percentage of Stock**
Pre 1940	227,000	14.14	3,322	14.14
1940-1960	284,000	17.69	4,156	17.69
1960-1980	541,000	33.71	7,917	33.71
Post 1980	553,000	34.45	8,092	34.45
Totals	**1,605,000**	**100**	**23,487**	**100**

When the age distribution is applied to the Palmerston North City housing stock for separate dwellings there is an estimated 15,000 separate standalone properties built prior to 1980 which may have some lead-based paint. The level of maintenance and method of renovation of structures painted with lead-based paint can have a significant impact on the soil lead concentrations (O'Connor et al, 2018; Turner & Lewis, 2018). Owner occupied properties are likely to undergo a more regular maintenance regime while rental properties may be left to a poorer condition (Jacobs et al, 2002; McClintock, 2015). In

2013, 58% of dwellings in Palmerston North City were owned or held in family trust with the remainder in the rental market or unspecified, similar to the 60% private ownership seen nationally (Statistics New Zealand, 2013). The more paint flakes that fall onto the soil and are not cleaned up during a renovation or repainting, the higher soil lead concentrations become, so behaviour of the contractor or homeowner can have a direct influence soil lead concentrations (McClintock, 2015). McClintock (2015) showed that lead concentrations could also be correlated with social indicators such as income, with lower income homes being more deteriorated state and therefore more likely to exhibit increased soil lead concentrations. The study by McClintock (2015) demonstrated that there are wider social implications of environmental lead in the residential environment that may disproportionately impact those that arguably can least afford to deal with it.

2.2.4 Soil Lead Exposure Pathways

Lead in the soil, dust, air and structures within the residential, urban and suburban environment does not, by its presence, create a risk. For lead exposure to occur there needs to be a complete exposure pathway between a source of lead in the environment, a method of exposure (pathway) and a sensitive receptor (Ministry for the Environment, 2011a).

2.2.4.1 Environmental Exposure

In consideration of environmental exposure, lead is not particularly mobile in soil when compared to other organic and inorganic compounds (Ministry for the Environment, 2011a). In residential soils which are commonly characterised by a neutral pH and high organic carbon, there is not expected to be a significant level of lead leaching (Ministry of

Health, 2012). Lead in soils has been shown to affect reproductive ability in New Zealand invertebrates such as *Folsomia candida* at concentrations as low as 35mg kg^{-1} and toxicity for soil microbes at concentrations of 49 mg kg^{-1}(Landcare Research 2016). The ecological soil guideline value (Eco-SGV) for lead for the protection of 95% of species is set at 796 mg kg^{-1} for fresh lead or 1276 mg kg^{-1} for weathered lead (Landcare Research, 2016). Deteriorated or renovated lead-based paints fall into the latter weathered lead category in most residential scenarios. A good indicator of ecological health in the residential setting is the presence or absence of infaunal species such as earthworms and other insects. Especially in cultivated areas around the dwelling such as gardens that have high organic matter and regular soil mixing the presence or absence of common species such as earthworms may give an indication of ecological impacts of residential activities. However, there is limited research investigating the ecological impact of lead-based paint contamination in residential landscapes. This is likely to be two pronged with the greater, more visible risk to human occupants being perceived as of greater importance, and, residential ecosystems being regarded generally as having less ecological value compared to areas such as reserves and wild spaces that traditionally receive conservation and environmental focus.

2.2.4.2 Human Exposure

Exposure occurs both outside the home when people are directly exposed to contaminated soils, and within the home as dust within a house is comprised of predominantly exterior sources that have been suspended or tracked in (Jordan & Hogan, 1975; Laidlaw et al, 2017). Ingestion of contaminated soils and dust is thought to be the dominant exposure pathway for lead to humans (Kandic et al, 2019; Ministry for the Environment, 2016). Other exposure pathways such as inhalation may play a bigger role than has been assumed to date but further research is required to properly assess the risk (Laidlaw et al, 2017). The importance of quantifying lead exposure pathways in the residential setting is reinforced by studies examining lead concentrations in house dust which has been correlated to external soil concentrations of lead (Jacobs et al, 2002; Jordan & Hogan, 1975). Jordan and Hogan (1975) showed that higher soil lead concentrations were directly linked to increased lead concentrations in household dust. Lead exposure can also occur through lead in drinking water from lead fittings, pipework and airborne lead from leaded fuels or industrial emissions (World Health Organization, 2016). Airborne and soluble lead exposure pathways will not be discussed further here as the current research focusses on soil lead in particular.

Lead-based paint does not pose a risk when in good condition and on a sound surface, it is only when it becomes damaged or deteriorates that exposure can occur (Ministry of Health, 2012). Deterioration and damage to lead-based paint occurs mainly through renovation and demolition of the structure it is applied to, or through natural deterioration of the paint over time (Laidlaw and Filippelli, 2008; Ministry of Health, 2012). The deteriorated or removed lead-based paint then falls onto the soil surface in flakes ranging in size from dust particles to larger sheets. The magnitude of transfer to soil depends on the thickness of the applied coats and the method of deterioration/removal (United States Environmental Protection Agency, 1995). Historically, lead-based paint was burnt off which generated very fine particles within the soil matrix (Jordan & Hogan, 1975). Studies have shown that dispersal is limited to 1-2 meters from the painted surface and is highest in the topsoil directly below the deteriorating paint because of lead encapsulated in flakes of paint (Codling, 2013; Ministry of Health, 2012; O'Connor et al, 2018; Turner & Lewis, 2018). It is unlikely that the soils beneath the house will have elevated lead concentrations unless soil is moved under the house from exposed areas (Jordan & Hogan, 1975). The condition and use of the soil beneath soil-deposited deteriorating paint also influences soil lead concentrations. Turner and Lewis (2018) showed that vegetative groundcover improved the dispersion of flaking paint with lower concentrations over a greater distance, while other studies have shown that the presence of grass cover increases the amount of lead-based paint deposited per area (Fergusson, 1986). Disturbance of the soil in vegetable or ornamental gardens where lead deposition has occurred may also aid the dispersion of lead-based paint flakes both horizontally and vertically (Public Health England, 2019; Rouillon et al, 2017). Lead rich 'horizons' may be present as renovations or damage often occurs periodically causing lead-based paint to be deposited onto the surface soils in discrete events sometimes decades apart but in significant volumes (Ministry of Health, 2012). This horizon is then buried by soil addition or changes to the site landscaping, leading to cases where lead concentrations may in fact be greater at depth than on the surface, especially in well mixed garden soils (Jordan & Hogan, 1975; Ministry of Health, 2012). Statistics New Zealand (2013) census data indicates that in Palmerston North City there are 64,491 people living in separate standalone houses representing 81% of the population, similar to the national trend of 79%. The usual number of occupants in these households varies but the majority of homes have one, two, three or four usual occupants, with approximately 4,000, 8,000, 4,000 and 4,000 standalone dwellings for each number of occupants respectively (Statistics New Zealand, 2013). In Palmerston North City, approximately 10,000 occupants of these dwellings are under the age of ten and 20,000 occupants under the age of 20 (Statistics New Zealand, 2013). Statistics New Zealand (2013) data also shows that 60% of these standalone home were built prior to 1980 and are therefore highly likely to have lead-based paint (United States Environmental Protection Agency, 1996a) in which roughly 12,000 occupants under the age of 20 or 15% of the population of Palmerston North City are occupiers. This proportion of people under twenty years of age occupying homes where lead-based paint is representative of the wider national picture (Statistics New Zealand, 2013) and gives an indication of the potential exposure levels for the population subgroup most likely to be impacted by exposure to elevated lead levels (World Health Organisation, 2016).

Lead readily sorbs to finer particles making it easier for re-suspension in dry windy conditions (Laidlaw and Filippelli, 2008) or to adhere to the skin, clothes and footwear of occupants (Clark & Knudsen, 2014; Paltseva et al, 2019). Lead-based paint that deteriorates onto receiving soils has been shown to contribute to house dust lead concentrations, although the significance of this contribution appears to vary and is readily influenced by human behaviours (Jordan & Hogan, 1975; Kim and Fergusson, 1992; Laidlaw and Filippelli, 2008). Lead contaminated soil can be brought into the home on footwear and clothing as well as on skin and pets that move between indoors and outdoors (Laidlaw et al, 2018). A recent study by Laidlaw et al (2018) also demonstrated that there may be seasonal variation in exposure due to resuspension of finer soil particles during hotter and dryer periods when low soil moisture prevails. Gardening activities are another common exposure pathway between soil lead and occupants of residential properties (Public Health England, 2019; Rouillon et al, 2017). In New Zealand and around the world, there is increasing importance on food provenance resulting in increasing levels of home gardening and vegetable production within residential urban soils (Mahar et al, 2015; Public Health England, 2019). Exposure to soil with elevated lead concentrations can occur when gardeners directly track contaminated soil into the home on clothing and skin, particularly hands, or by consumption of vegetables that have lead contaminated soil on them (Kandic et al, 2019; Paltseva et al, 2018; Rouillon et al, 2017). Lead is not as readily taken up by plants as other metals such as cadmium and iron, so consumption of the vegetable itself may not represent a significant exposure pathway (Hettiarachchi and Pierzynski, 2004; Kandic et al, 2019). However, a recent study by Paltseva et al (2018) demonstrated that root vegetables such as carrots and radishes did uptake lead when grown in soils with highly elevated lead concentrations. They showed that lead concentrations in the tissue of vegetables grown in contaminated soils were elevated above recommended European Union (EU) guidelines for lead in root crops intended for human consumption (Paltseva et al, 2018). It is possible that consumption may be a significant exposure pathway in households where home grown vegetable consumption is greater than average. In root vegetables such as carrots, potatoes and parsnips, contaminated soil can also adhere to the crop and be brought into the home and if not cleaned thoroughly can then be ingested (Paltseva et al, 2018). For leafy vegetables such as lettuce and spinach, contaminated soil may become lodged between leaves during gardening activities or from rain splash displacing soil particles (Paltseva et al, 2018; Public Health England, 2019; Rouillon et al, 2017). For other garden vegetables such as tomatoes, brassicas and citrus there is a lesser likelihood of adherence of contaminated soil simply because of the decreased proximity to the soil (Hettiarachi and Pierzynski, 2004; Rouillon et al, 2017).

Soil is considered to be both a sink and a source for lead in residential scenarios and has been directly shown to increase house dust lead concentrations and blood lead levels (Jordan & Hogan, 1975; Laidlaw et al, 2017; Ministry of Health, 2012; United States Environmental Protection Agency, 1995). The degree of exposure and severity of symptoms in humans has been correlated with soil lead concentrations, human behaviour, physiology such as size and age, soil properties and bioavailability (Laidlaw et al, 2017; Kandic et al, 2019; Ministry of Health. 2012; Paltseva et al, 2018).

2.2.5 Bioavailability and Bioaccessibility

The final step in the human exposure pathway is the absorbance of lead into the body following ingestion, inhalation or dermal contact. Ingestion is the dominant exposure pathway for lead and once consumed it passes through the human gastrointestinal system with the bulk of absorption occurring within the stomach and small intestine (Appleton et al, 2013; Ruby et al, 1996). The amount of a contaminant that is absorbed across a biological membrane as a fraction of the total lead within an ingested substance is termed the bioavailability (Ministry for the Environment, 2016). Bioavailability of lead is important to understand as it determines the acceptable concentrations of soil lead that humans can be exposed to without exhibiting chronic or acute symptoms (Ministry for the Environment, 2016; Nigg et al, 2008). The current soil guideline value for soil in New Zealand is the highest concentration of soil lead that will not cause adverse effects to an exposed human, however it assumes 100% bioavailability which may be too conservative (Ministry for the Environment, 2011a; Ministry for the Environment, 2016). The testing for bioavailability is expensive, time consuming and must be strongly correlated to apply 'in human' exposure scenarios (Juhasz et al, 2013). For these reasons *in vitro* assays designed to replicate human gastrointestinal exposure to lead and other contaminants have been developed (Ministry for the Environment, 2016). These assays assess bioaccessibility which is an estimate of a certain contaminant's bioavailability using a relatively inexpensive and quick test in lieu of more onerous *in vivo* experiments (Ruby et al, 1996; Smith et al, 2011). Common soil properties such as total organic carbon, contaminant source and clay content can significantly influence the bioavailability of soil lead (Clarke et al, 2015; Yan et al, 2015). Lead bioaccessibility has been shown to increase with clay content, total lead concentrations, and decreasing particle size, and decreases with increasing levels of organic carbon and phosphates (Freeman, 2012; Laidlaw et al, 2017; Smith et al, 2011; Yan et al, 2019). A study by Codling (2013) showed that bioaccessibility of lead from a paint source increased with lower concentrations, indicating that site specific conditions have a strong impact on bioavailability of lead. Other soil properties such as soil pH increases lead leachability and bioavailability with lower pH, however the pH levels required to significantly increase bioavailability are unlikely to be present in a typical residential environment (Golder Associates, 2012; Yan et al, 2015). Lead bioaccessibility has been well researched with studies reporting a range of bioaccessibility from an extremely low 3% (Turner & Lewis, 2018) to an unexpectedly high 78% (Golder Associates, 2012). Most studies have shown that lead bioavailability can be expected to be between 40-60% of total soil lead concentrations, but this varies significantly between sites and requires site specific assessment to be accurately determined (Gaw et al, 2008; Ministry for the Environment, 2016; Yan et al, 2019). The bioavailability of soil lead can be used to inform human exposure risk when assessing remediation and mitigation options for lead impacted sites (Clarke et al, 2015; Ministry for the Environment, 2016; United States Environmental Protection Agency, 2007; United States Environmental Protection Agency, 2012; Yan et al, 2015). Although New Zealand does not currently allow for the use of bioavailability in contaminated land risk assessments, it is expected that New Zealand regulation will eventually follow the United States where a method of calculating bioaccessibility is approved for use in contaminated land risk assessments (Ministry for the Environment, 2016; United States Environmental Protection Agency, 2007; United States Environmental Protection Agency, 2012). The creation of a standardised bioaccessibility test that can be relied on has the potential to reduce remediation costs for sites that while having high lead concentrations in the soil, may have low bioavailable, and this would increase the permissible total concentration onsite, effectively diverting waste from landfills (Golder Associates, 2012; Ministry for the Environment, 2016; Ruby et al, 1996). Bioaccessibility and bioavailability, although considered important for assessing the risk of exposure to soil lead concentrations, is outside of the scope of this research and should be the focus of further study to better understand the potential exposure risk posed by the findings presented of the current research.

2.3 Regulatory Focus

Soil contaminants such as lead and arsenic have come under increasing scrutiny from regulators as housing development takes over previously horticultural land. The source of contaminants like lead plays an important role in determining bioavailability (Golder Associates, 2012; Yan et al, 2019). Contaminated land in New Zealand is primarily identified using the Ministry for the Environment's Hazardous Activities and Industries List (HAIL), which is a list of potentially polluting activities or industries compiled to aid contaminated land risk assessment (Ministry for the environment, 2011d). A recent study by Seyefardalan et al (2017) within Christchurch City compared soil samples from HAIL sites (former orchards) developed into housing, and older residential neighbourhoods within the red zone following the 2011 and 2015 Christchurch earthquakes. The findings demonstrated that the houses on the HAIL sites had concentrations significantly lower than the residential properties with no previous HAIL, highlighting that a substantial amount of residential land is likely contaminated from lead-based paint and other household level impacts such as garden sprays, leaded petrol, and pesticides. An older investigation by Jordan & Hogan (1975) investigated 347 properties within Christchurch following a case of lead poisoning in children and found that 38% of residential properties were contaminated above the then regulatory limit of 300mg kg^{-1} (Jordan & Hogan, 1975).

Landowners are responsible for meeting requirements under the Resource Management Act (1991) (RMA) through land use consents to remediate or manage land to an acceptable contaminant level for the land use. Currently, New Zealand manages the regulation of soil contaminants through the National Environmental Standard for Assessing and Managing Contaminants in Soil to Protect Human Health (Ministry for the Environment, 2011b). The national standards set specific soil guideline values for specific contaminants such as lead using exposure scenario information (Ministry for the Environment, 2011b). These regulations do not allow for bioavailability or bioaccessibility to be taken into account on the basis that there is not enough scientific evidence or local experience to support this on a site by site basis. There has only been one instance of a site specific risk assessment involving bioaccessibility in New Zealand that has been accepted by regulators which was for a mining soil impacted subdivision in Thames, Waikato (Golder Associates, 2012). Incorporating bioavailability and bioaccessibility as part of human health risk assessment could reduce the costs of developing or remediating contaminated land and provide a better estimate of the actual risk to both the environment and people by incorporating site specific conditions into land planning (Ministry for the Environment, 2016).

2.3.1. Soil Lead Guidelines

Heavy metals in soils in many countries around the world are managed according to the risk they pose to human health and the environment. In New Zealand, the management of contaminated land is legislated by the Resource Management Act (1991) and the National Environmental Standard for Assessing and Managing Contaminants in Soil to protect

Human Health (Ministry for the Environment, 2011b). Accompanying these regulations are guidance documents which define Soil Guideline Values (SGV) for twelve priority contaminants including lead, and a methodology for deriving any SGV that are not defined (Ministry for the Environment, 2011a). As a priority contaminant, the soil guideline value (SGV) for lead has already been determined and varies based on different land use scenarios, each representing a different level of exposure and therefore risk (Ministry for the Environment, 2011a). There are five standard land-use scenarios defined by the Methodology (Ministry for the Environment, 2011a); rural/lifestyle block, standard residential, high density residential, parks/recreational and commercial/industrial.

Each scenario is defined based on a presumed level of exposure that takes into account differences in production of home grown produce, typical occupant of the site, average exposure time and overall risk to the user (Ministry for the Environment, 2011a). The rural scenario assumes that 25% of produce consumed by site users is home grown. This can vary between 10-50% and should be considered on a site by site basis (Ministry for the Environment, 2011a). The standard residential scenario estimates that 10% of produce consumed by the occupant will be home grown and is presumed to be the main exposure pathway. High density residential assumes that no home grown produce is consumed and there is limited garden area (Ministry for the environment, 2011a). The park and recreational scenario accounts for low exposure activities such as walking but also higher activities such as sports where contact and exposure to dirt is more common. Soil ingestion is the main consideration in this scenario and the levels can be considered conservative for passive recreational activities (Gray and McLaren, 2006; Ministry for the

Environment, 2011a). The final scenario considered is commercial and industrial which often includes significant paved areas, large building footprints, and assumes very low exposure to soil but higher volatile contaminant concentrations (Ministry for the environment, 2011a). This does not include excavation work, but does discriminate between indoor and outdoor workers, assuming that an outdoor worker will experience greater exposure. The Ministry for the Environment (2011a) has defined soil guideline values for lead under the different scenarios shown in Table 2.3.

Table 2.3 Soil Guideline Values in mg kg^{-1} for total lead in different land use scenarios. Adapted from "Methodology for deriving standards for contaminants in soil to protect human health" by Ministry for the Environment, 2011a, Wellington: Ministry for the Environment.

Land Use Scenario	Combined Soil Contaminant Standards (mg kg-1)		
	No Produce	**10% Produce**	**25% Produce**
Rural Residential/Lifestyle Block	250	210	160
Standard Residential	250	210	160
High-density Residential	500		
Recreational	880		
Commercial/Industrial Indoor Worker	NL		
Commercial/Industrial Outdoor Worker/maintenance	3,300		

Most standard residential properties are likely to have some level of home grown produce in New Zealand and it is generally assumed that 10% produce is a reasonable assumption for assessing risk (Rouillon et al, 2017). The lead SGV of 210mg kg^{-1} for this scenario applies to 76% of New Zealand Housing stock and 78% of the housing stock in Palmerston North City (Statistics New Zealand, 2013). The recreational and commercial/industrial exposure scenarios will not be considered in detail here as they are not applicable to urban and suburban residential properties. The New Zealand lead soil guideline value of 210mg kg^{-1} for residential properties is conservatively low when compared to other jurisdictions such as Australia and the United Kingdom where the limit for lead in residential soils is 300mg kg^{-1} and 450mg kg^{-1} respectively (Kandic et al, 2019; Ministry for the Environment, 2011; Turner & Lewis, 2018). Other western countries such as the United States have a much less conservative risk-based approach, limiting soil in children's play areas to 400mg kg^{-1} and a maximum limit of 1200mg kg^{-1} for other areas of bare soil, notably excluding grassed areas (United States Environmental Protection Agency, 2019a). There are other guidelines in New Zealand that limit lead levels for environmental protection such as the Soil Guideline Values for the Protection of Ecological Receptors (Eco-SGVs) which are set at 796mg kg^{-1} for fresh lead or 1276mg kg^{-1} for weathered lead (Landcare Research, 2016). It is important to note that the Eco-SGVs are not legislated (the limit for the protection of human health is), and instead are a guideline value. However, they are commonly used by regulators in New Zealand to assess likely impacts on the environment.

2.3.2 Regulation of Lead in Products

There is no standard international regulatory agreement for managing lead globally, with individual countries setting their own lead standard for various products and the environment. This includes lead-based paints and the lack of global regulation has caused difficulties in managing the complete phase out of lead based paint, where this is the goal (O'Connor et al, 2018). Lead has been used in commercial, industrial and domestic consumer products for more than a century (O'Connor et al, 2018). Most western countries regulate the addition of lead in consumer products, especially those where exposure is most harmful such as in children's toys and internal paint products (O'Connor et al, 2018). In New Zealand, the phase out of lead in paint began in 1945 when white lead and lead sulphate were banned from paints intended for residential end use (Jordan & Hogan, 1975; Ministry of Health, 2012). However, other additives such as lead chromate remained in use for brightly coloured paints well into the 1980's and possibly as late as the 1990's (Ministry of Health, 2012). Figure 2.1 shows that as lead paint regulation was removing lead compounds from paint, lead was increasingly being used as an additive in leaded petrol and gasoline (Ministry of Health, 2012). Although lead in the form of tetraethyl lead (TEL) had been used in fuels since the 1920's, the impact on the environment only became noticeable with the rise in popularity of the motor vehicle (McClintock, 2015; Smith et al, 2011). Lead was eventually removed from fuels in the late 1990's and early 2000's worldwide, however an estimated 4-5 million tons of lead had been emitted over the lifetime of its use in the United states alone (Figure 2.1) (Laidlaw and Filippelli, 2008).

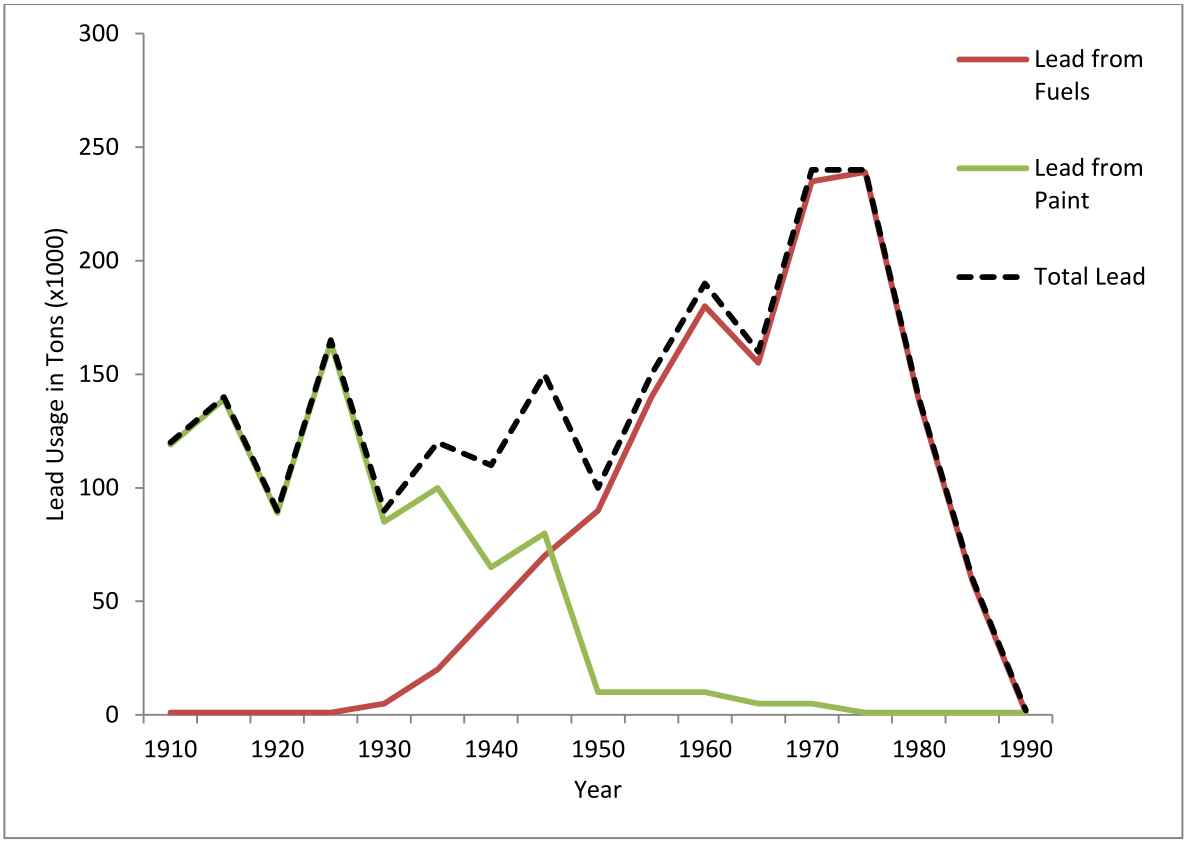

Figure 2.1. Estimated lead usage in tons as additives in paint and gasoline within the United States. Reproduced from "Resuspension of urban soils as a persistent source of lead poisoning in children: A review and new directions," by Laidlaw M. & Filippelli, G. (2008). *Applied Geochemistry, 23*, 2021-2039.

2.3.3 Blood Lead Levels

The notifiable blood lead level in New Zealand is currently set at 10µg/dL, equivalent to 0.48µmol/L (Ministry of Health, 2012). On average there are 143 notifications per year in New Zealand, however this may not be an accurate reflection of the problem as many cases go undetected or are misdiagnosed (Ministry of Health, 2012). This is the same level as Australia but twice the notifiable blood lead level of some other western countries such as the USA (5µg/dl) (Centre for Disease Control and Prevention, 2019; Ministry of Health, 2019; State of Queensland (Queensland Health), 2018). In New Zealand, the Ministry of

Health (2019) has recently begun a consultation with the aim of reducing the notifiable blood lead level from 10µg/dl to 5µg/dl stating “There is an increasing body of evidence that shows adverse health effects in children and adults at blood lead levels below 0.48µmol/l (10µg/dl)” (Ministry of Health, 2019). Currently, if a person exhibits a blood lead level above the notifiable standard this triggers actions specified in the Ministry of Health’s guidelines; ‘the environmental case management of lead-exposed person: guidelines for public health units’ (Ministry of Health, 2012). This requires certain precautions to be taken at the affected persons property in order to remove or manage the sources of lead so that exposure is limited or stopped (Ministry of Health, 2012). If the notifiable blood lead level is decreased, it could result in an increased number of cases, providing further impetus for research and regulation of residential lead exposure.

2.4 Purpose of the Study

2.4.1 Hypotheses to be Tested

The aim of this research is to investigate the vertical and horizontal distribution of lead within soils of residential properties. It is hypothesised that lead-based paint is a significant contributor to soil lead concentrations in the urban and suburban environment of regional New Zealand cities. Additionally, it is hypothesised that the concentrations of lead in residential soils will decrease with depth and distance from structures currently or historically painted with lead-based paint.

2.4.2 Reasons for the Research

The research presented in this thesis provides a spatial investigation into lead concentrations within residential soils of a regional New Zealand city, Palmerston North. Previous research has focussed predominantly on major urban areas such as Los Angeles, Plymouth, Melbourne and Sydney (Clarke et al, 2015; Laidlaw et al, 2018; Rouillon et al, 2017; Turner & Lewis, 2018). These cities have a historical industrial legacy as well as a population pressure that is absent from many regional cities of New Zealand. This research has been undertaken to fill a gap in the current knowledge by investigating residential urban and suburban soils in a regional New Zealand city with limited industrial and agricultural history when compared to major overseas urban centres. An intention of the work is to compare the findings of this research to the trends and pollution sources seen in larger urban areas so that residential lead-based paint contamination can be better understood. The research undertaken required ethical considerations with regards to participant health, and confidentiality of personal data. The measures and precautions used to address these ethical considerations are discussed in detail in Chapter Three.

2.5 Structure of this thesis

The research presented in this thesis is a thorough investigation into the spatial distribution of lead within residential soils, focusing on lead-based paint as the dominant source of lead in soil in the residential setting.

The following chapters detail the methods used to identify properties for investigation, undertake the soil sampling and conduct the analyses for determination of soil lead concentrations. The results are presented and discussed in two chapters and it is important to note that the locations and other identifying features of all sample properties have been removed from the final presented data to preserve the privacy of the study participants. Firstly, an initial investigation was undertaken, collecting samples from 34 properties of varying ages, construction types, locations, traffic volumes and building condition. The findings of the initial investigation are presented and discussed in Chapter Four. A detailed case study investigation was then undertaken on three properties that exhibited high soil lead concentrations in the initial investigation. This detailed investigation examined the distribution of lead in soils at varying depths and distances from the house and other painted structures. The results of the detailed investigation are presented and discussed in Chapter Five. Chapter Six is presented as a general discussion of the research including both the initial and case study investigations. This chapter will focus on the implications of the findings of this current research and provide recommendations and potential solutions with reference to the findings of Chapters Four and Five. Finally, the findings of this research will be discussed in relation to the current regulatory and risk assessment framework and how any deficiencies or conservative approaches may be addressed in the future.

3.0 Methodology

3.1 Introduction

The condition of residential soils within the urban New Zealand environment is relatively unknown when compared to industrial and agricultural soils due to a lack of environmental quality research on urban soils (Landcare Research, 2015). To conduct the research described in this thesis, methodology has been adopted from overseas examples in similar small urban environments. The aim of the research was to identify the spatial distribution patterns of lead concentrations within residential surface soils, and therefore soil sampling was undertaken in accordance with the Ministry for the Environment guidelines for managing contaminated land (Ministry for the Environment, 2011c). In this section the study location of Palmerston North City is introduced and the analytical methods used for the initial and case study investigations are described.

3.1.1 Site Setting

Palmerston North City is the largest city of the Manawatū-Whanganui region in the North Island of New Zealand (Figure 3.1). For the purposes of the current research, Palmerston North City refers to the urban area of Palmerston North and excludes the rural areas around Linton and Turitea that are included within the wider district of Palmerston North City.

Figure 3.1 Location of Palmerston North within New Zealand (source Google maps, 2019)

Palmerston North City is New Zealand's eighth largest urban area. The City was formally established in 1866 with pastoral farming and forestry being the dominant industries (NZ History, 2019). In 1911 the population was estimated at 10,000 and had doubled to 20,000 by 1927 (NZ History, 2019). Palmerston North City currently has an estimated population of 88,700 as of June 2018 and is expected to reach 100,000 by 2033 (Statistics New Zealand, 2013).

Palmerston North City is located on a coastal plain at the point where the river terrace landscape gives way to river flats (Cowie, 1977). The urban area of the city borders the western bank of the Manawatū River and is generally flat with occasional terraces. To the east of the Manawatū River is the residential suburb of Fitzherbert and Massey University campus. The soils in the study area fall generally into two categories, terrace soils and river flat soils. The terrace soils are present east of the Manawatū River and are composed of the Tokomaru, Milson and Halcombe series as defined by Cowie (1977). Terrace soils are characterised by a neutral pH with low phosphorus and moderate organic matter; these range from silty-sandy loam with gravel horizons (Cowie, 1977). The majority of the Palmerston North City urban area is underlain by the Manawatū series which ranges from well to poorly drained silty, sandy loam with moderately acidic topsoil (Cowie, 1977). The Kairanga and Te Arakura series present on the river flats north-west of the city are generally poor draining with higher organic matter than the Manawatū series (Cowie, 1977). The central city is dominated by a stoney unit of the underlying Ashurst series creating a very well-draining moderately acidic soil (Cowie, 1977). Much of the current urban area, especially newer suburbs like Awapuni, Hokowhitu, and Roslyn were built on productive land formerly used for dairying, orchards and market gardens (Cowie, 1977). Work undertaken by Landcare Research (2015) compiled background concentrations of many common elements for the soils of New Zealand, including Palmerston North City. For lead, the background concentration (95th quantile) at the sampling sites in this study ranges from 25.83mg kg^{-1} to 46.71mg kg^{-1} with the lower values predicted for the majority of sites within the main urban centre and higher background concentrations expected on the eastern terraces (Landcare Research, 2015).

3.2 Initial Multiple Property Investigation

3.2.1 Selection of properties

The locations targeted by the initial investigation were standalone residential properties of any construction type built prior to 1980. Owners of potential properties were contacted through email advertising within Massey University's postgraduate and staff network. The advertisement invited participation in this study for the purposes of gathering soil samples from properties. The advertisement began the filtering process by requesting that any participants must be an owner occupier and the house must be built prior to 1980 with areas on at least two sides of the house available for soil sampling.

All respondents were then contacted and provided with an information sheet (Appendix 1) and a participant consent declaration. The information sheet provided additional information regarding the details of the study and the potential impacts that it could have on participants. The participant consent declaration was a compulsory document for ethics considerations within this study and ensured that both the participants and the researcher were informed and could not be held responsible for impacts arising from this research. The participant consent declaration confirmed that all sample results and personally identifiable information such as address, name and ownership details were to be kept confidential and destroyed following publishing of this Thesis. Properties were selected if the house was first constructed prior to 1980 and located within the urban area of Palmerston North City. The distribution of the properties included in the study was random due to the mode of participation. Only owner occupier properties were included in the study due to confidentiality and privacy reasons.

3.2.2 Sampling Pattern

The initial investigation was undertaken to investigate lead-based paint contamination at a population level across Palmerston North City. To achieve this, between 7 and 12 composite samples were collected from the topsoil (0-10cm) around the house curtilage of participant properties. The sample locations within each property were chosen based on similar international studies. Sample locations were distributed using a systematic sampling pattern around all four sides of a property. Each house varied in construction and layout of features such as driveways, entrance ways, window frames and sheds. The variation influenced the sampling locations on each individual property. The standard approach taken was to have three equally-spaced sample locations along each side of a property. Where possible, each sampling location was within 1m of the house. Where driveways, paved areas or decking extended for greater than 1m away from the property then this was noted in the sampling field notes. The equal spacing of sample locations along each side of a house was flexible to account for inaccessible areas or other structures that impeded sampling. Samples were collected from an area of exposed or lightly vegetated soil, such as grassed, planted with ground cover, or bare soil. No samples were retrieved from beneath hardcover. The characteristics of each sample location were recorded through photographs and descriptive records as part of the sampling procedure described below. Approximate sample locations were identified on a property map for future reference and if return visits needed to be undertaken. The soil samples were collected from the surface soil layer, no deeper than 10cm.

3.2.3 Soil Sample Collection

Following identification of the sampling location outlined in section 3.2.2, the following steps were completed to collect each soil sample.

1. A photo of the sample location and observations of the date, time, weather conditions, location description, sample number, property ID, and soil description were all recorded in the field sampling sheet.
2. The soil samples were taken using a 10cm stainless steel soil corer with a foot press.
3. The soil corer was decontaminated between sampling locations using fresh water and a pipe scrubber to clean any dirt from inside the corer.
4. The soil corer was pushed into the soil of the sample location for the full length of the tube. The corer was twisted slightly to loosen the core and then extracted.
5. Using gloved hands, the soil core was emptied into a paper sample bag ensuring that the entire core is collected.
6. A composite sample was gathered at each sample location by repeating steps 3, 4 and 5 a total of three times, combining all three cores within a single sample bag.
7. Using a permanent marker, the sample bag was labelled with the sample ID, property ID and date/time of sampling.

The sample was then placed in a large plastic container with other samples for delivery to the laboratory. The samples were kept in paper bags, upright, within a larger sealed plastic box to ensure that the samples were not compromised during transport and to minimize contamination between samples. The samples were delivered by the researcher to the lab at the end of every day of field work and secured within the laboratory prior to analysis.

3.3 Case Study Property Investigation

3.3.1 Selection of properties

Following the initial multiple property investigation, a case study investigation into three properties was undertaken to in order to delineate the vertical and horizontal distribution of lead across the properties. The properties selected were those that showed elevated concentrations of soil lead during the initial investigation as this was deemed most likely to provide a distinct distribution pattern. Consideration was also given to the availability of sampling locations around the selected property as sealed areas may have altered the distribution pattern through a sampling location bias. As the property was chosen from the initial sampling round, no further ethical considerations were required. The property owner's permission was verified prior to undertaking the additional sampling.

3.3.2 Sampling Pattern

Systematic, horizontal grid sampling at different depths was selected as the appropriate sampling regime in order to comprehensively characterise the distribution of lead within soils around the selected properties. The grid sampling with a minimum of 100 samples was used instead of transects as in Clark and Knudsen (2014) and Jordan and Hogan (1975) to capture the distribution of lead across the entire property at a higher resolution. A $2m^2$ systematic grid of sampling locations was marked out starting from the roadside to the back of the property. The berm was included to assess any potential impact from historical use of leaded petrol that may be present. At each location, a sample was taken using a 2cm diameter, 30cm length soil corer by pushing and twisting the corer into the ground. The corer was then removed and care was taken not to scrape soil from the sides of the hole during removal. The sample core was extracted from the corer and divided into three separate samples at 0-10cm depth, 10-20cm depth and 20-30cm depth. Attempts at sampling a lower depth of 20-30cm was largely unsuccessful as the hand auger used to retrieve the soil samples was unable to pass through the lower substrate. At most locations, the soil was only sampled to 20cm depth with harder fill/substrate beneath, presumably from when the house was first constructed. This methodology was selected to provide a vertical and horizontal distribution pattern across a selected residential property.

3.3.3 Soil Sample Collection

Following identification of the sampling location outlined in section 3.3.2, Steps 1 to 6 below were followed to collect the each soil sample.

1. A photo of the sample location and observations of the date, time, weather conditions, location description, sample number, property ID, soil description were all recorded in the field sampling sheet appended.
2. The soil samples were taken using a 30cm stainless steel soil auger.
3. The soil corer was decontaminated between sampling locations using fresh water and a pipe scrubber to clean any dirt from inside the sampler.
4. The soil corer was pushed into the soil of the sample location for the full length of the tube. The corer was twisted slightly to loosen the core and then extracted.
5. Using gloved hands and a stainless steel trowel, the soil core was divided into 0-10cm depth, 10-20cm depth and 20-30cm depth sections which were then placed into paper soil sample bags.

6. A permanent marker was used to label the sample bag with the sample ID, depth, property ID and date/time of sampling.

3.4 Health, Safety and Confidentiality Considerations

3.4.1 Health and Safety Considerations

Health and safety considerations were considered for both the sampler and the participant. The soils sampled were of an unknown quality so precautions were taken to reduce exposure to the participant and the researcher during sample collection and analyses. Human exposure to lead is predominantly through ingestion of soils so the following measures were taken to limit any potential exposure to disturbed soils (Ministry for the Environment, 2011a). During sampling the researcher wore latex or nitrile gloves, a dust mask, and dedicated field sampling clothing. Hand cleaner was used to ensure that all dirt was removed from the samplers hands where accidental contact may have occurred. Disturbing the soil during sampling potentially increases the exposure of the property owner to the soil on their property. This study did not alter the concentration of any contaminants within the soil and the sampling does not increase the level of exposure. The use of a soil corer to retrieve the samples minimized the soil disturbance and all sample holes were backfilled with new potting mix to cover any exposed soil, limiting the exposure pathway. If the property owner requested the sample results, then additional information was provided on where to seek advice and information around lead in soils and human exposure. The property owner was directed to the Ministry of Health website that provides information regarding lead in soils and lead-based paint. It is outside the scope of this study to make recommendations for protection of human health specific to the sampled properties. Additional considerations relating to sampling included locating buried services; most properties are likely to have at least one water and electricity main line, no sampling was undertaken near any services, additionally the soil sampling auger used only penetrates to 30cm depth and most services are expected to be buried to >60cm under current building compliance codes so it is considered unlikely that any contact will occur.

3.4.2 Confidentiality

The sampling of soil on residential properties was undertaken in accordance with the confidentiality agreement between the research team and the property owner/occupier. The confidentiality agreement (Appendix 2) stated that the soil sample results would be made available to the owner of the property if requested and any identifying or personal or property related information would be removed prior to publication. For publication of the Thesis, each property was assigned a property ID that replaced any identifiable information.

3.5 Soil Laboratory Analysis

3.5.1 Sample preparation

The samples were air dried in a Contherm Thermotec 2000 Oven set to 65 degrees Celsius until constant weight. To confirm the progress of the drying process, five samples were collected at random and weighed using a calibrated Mettler PM4000 digital scale, the weight was recorded and the sample returned to the oven. The samples were reweighed hourly until a stable weight had been achieved at which point the sample was considered dry. Once dry, each sample was passed through a 2mm screened brass sieve removing any rocks or organic matter such as roots, bark and leaf material. Any harder soil clumps were broken up using a clean mortar and pestle. The sieved samples were returned to the labelled sample bag and set aside for digestion. Observations were recorded for each sample noting presence of paint chips and other material within the soil.

3.5.2 Nitric Acid Digestion

To prepare the soil samples for lead analysis, a nitric acid digest of the soil sample was undertaken. The digest of soil samples was undertaken as per USEPA method 3050B relating to the acid digestion of sediments, sludge's and soils (United States Environmental Protection Agency, 1996b). Each soil sample was weighed out using a calibrated Mettler Toledo New Classic ML digital scale which is accurate to 0.0001g. A clean piece of 60mm by 60mm paper was placed on the scale and tared to 0.0000g. Using a clean plastic teaspoon, the sieved soil sample was placed on the paper on the scale weighing out approximately 1.00g, recording the actual weight of the sample to 4 decimal places. The soil was then placed into a clean 100ml glass boiling tube, labelled with the corresponding sample ID and placed into a tube rack. This process was repeated until every sample had been placed into a boiling tube. The plastic spoon was cleaned and a fresh piece of paper was used between every sample to avoid cross contamination. For quality control, 0.1 gram of NIST Standard Reference Material 2710 – Montana Soils was prepared for digestion parallel to each batch of collected samples (four in total)(National Institute of Standards and Technology, 2003).

Samples were digested in a fume hood, using a heating block, with 1:1 nitric acid and 30% hydrogen peroxide following the method of USEPA method 3050B (United States Environmental Protection Agency, 1996b). To make a 1:1 nitric acid solution, 500ml of nitric acid was added to 500ml of deionized water in a 1000ml beaker. Using a calibrated pipette with a clean nozzle, 10ml of the 1:1 nitric acid solution was added to each soil sample. The soil sample and the nitric acid solution were then mixed within each test tube by gently agitating the sample, and then placed on a heating block set to 100°C for 15 minutes. Glass funnels were placed on top of each test tube to reduce evaporation rates. After 15 minutes the samples were removed to cool down to room temperature. Concentrated nitric acid (5 ml) was then added to each sample and gently agitated before the digest tubes were returned to the heating block at the same temperature for another 30 minutes with glass funnels placed on top to reduce evaporation. After 30 minutes the tubes were again removed and allowed to cool to room temperature, before 2ml of deionized water and 3ml of 30% hydrogen peroxide was pipetted into each sample and gently agitated to ensure any sediment was suspended in solution. The samples were returned to the heating block at 100°C for another 30 minutes *without glass funnels.* Digest tubes were then again removed, allowed to cool to room temperature, and a further 1ml of 30% hydrogen peroxide was added. After gentle agitation to re-suspend any settled solids, the digest tubes were then returned to the heating block at 100°C without glass funnels and allowed to reduce until approximately 5ml remained. All samples were then removed from the heating block, and diluted to 50mL with deionized water. Each sample was filtered through Wattman 42 filter paper to remove sediment into a 35ml plastic container labelled with the corresponding sample number. Any excess sample and filter paper was treated as acid waste and neutralized with bicarbonate soda prior to disposal. From the 35ml container, a smaller 10ml container was filled and labelled with corresponding sample number. Each 35ml sample container was then capped and stored for future analytical requirements.

3.5.3 Trace Element Analysis in the 4100 MP-AES

Trace element analysis was performed on the sample digestions using an Agilent 4100 microwave plasma - atomic emission spectrometer (MP-AES). The 10ml sample tubes prepared earlier were placed into the 4100 MP-AES for analysis. Along with ten reference solutions of the following lead concentrations, 0ppm, 2ppm, 6ppm, 10ppm, 20ppm, 40ppm, 60ppm, 80ppm, 100ppm and 200ppm. The reference solutions were produced by diluting 1000ppm lead reference standard with 2% nitric acid to the required concentrations. The manufacturers recommended settings for trace metal determination in soils was used. Three replicates of each sample were analysed with a read time of three seconds per sample. The wavelength for lead was set at 405.781nm. The samples were analysed in four separate runs using the same settings and a digest of NIST Standard Reference Material 2710 – Montana Soil (highly elevated trace element concentrations) with a certified value of 5532 mg kg^{-1} (National Institute of Standards and Technology, 2003), the samples achieved a minimum 98% agreement rate with the certified value across all runs. The MP-AES performed a calibration using lead standard solutions before every analysis run. The reported results were then divided by the sample weight and multiplied by a dilution factor of 50 to give the total lead concentration by acid digest analysis for each soil sample in mg kg^{-1}. As lead is not volatile, no correction factor was applied to account for soil moisture.

4.0 Initial Investigation

4.1 Introduction

Unlike larger urban areas, where lead additives in fuels have been shown to be a significant contributor to lead concentrations (Clarke et al, 2015; Laidlaw & Filippelli, 2008) lead-based paint is thought to be the dominant source in smaller towns and cities (Clark & Knudsen, 2014; Codling, 2013). Lead-based paint contamination of soils in New Zealand has not been investigated to the same extent as other developed countries such as the United States (United States Environmental Protection Agency, 1995), Australia (Kandic et al, 2019; Rouillon et al, 2017) and the United Kingdom (Turner & Lewis, 2018).

The results of an initial investigation into lead-based paint contamination of residential soils within a regional New Zealand City are presented in Chapter Four. Population levels statistics generated from the data collected from the research in this chapter are presented alongside an analysis of correlations between lead concentration and other measured variables; house age, construction type, paint condition, road classification and sampling location.

4.1.1 Aims

The aim of the initial investigation was to investigate the soil lead concentration of residential properties. It is hypothesised that lead-based paint is a major contributor to total lead concentrations in residential soils. To test this hypothesis, between seven and twelve samples were collected from the topsoil around the immediate curtilage of 34 properties within Palmerston North City using methods described in Chapter Three.

Factors such as age of the house, construction type, paint condition, and traffic volumes on the adjacent roads were recorded at the time of sampling.

4.1.2 Statistical Analysis

Descriptive statistics for the initial investigation results were calculated using Microsoft Excel 2014. The mean lead concentration at each property was calculated from 6-12 samples collected at each property, while population statistics were calculated from all samples collected (n=316 from 34 properties). Significance testing and graphs of relationships between total soil lead concentrations and property variables were completed using Minitab19 software. Figures 4.1 and 4.2 were produced using Microsoft Excel 2014. One-way ANOVA tests were used to identify significant differences in lead concentration between the different variables presented and discussed in this chapter. Outliers were identified as concentrations greater than two standard deviations from the mean and were removed for analysis of the data (Wild and Seber, 1999). Any significant outliers found are discussed in further detail.

4.2 Results

4.2.1 Total Sample Population

Soil lead concentrations presented in this chapter are expressed as mg kg^{-1} unless otherwise stated. The soil guideline value referred to is the Ministry for the Environment's (2011a) soil contaminant standard for lead in a residential land use scenario with 10% produce unless otherwise stated. Descriptive statistics from the analysis of the total soil lead concentrations are shown in Table 4.1. The overall mean soil lead concentration for all samples was 642.7mg kg^{-1} with a standard error of 50.5mg kg^{-1} and a range of 11.5mg $kg^{-}1$ to 9571.0mg kg^{-1}. The total lead soil concentrations were compared to the Ministry for the Environment (2011a) soil guideline value (SGV) of 210mg kg^{-1} for a residential land use with 10% produce scenario. Of the 316 soil samples collected, 41.8% (132) exceeded the lead soil guideline value, 130 were between the background concentration and the SGV, and 17.0% (54) were below the background concentration (Figure 4.1). Table 4.1 provides statistics for the number of samples on a property that exceed the recommended soil guideline value. The maximum soil lead concentration was 9571.0mg kg^{-1} which was sampled from an older weatherboard property with poor paint condition. The concentration of lead in this particular sample is approximately 1% of the soil mass, likely caused by the presence of paint flakes within the analysed sample. The minimum soil lead concentration recorded in the current study was 11.5mg kg^{-1} which was sampled from a mid-century weatherboard property with average paint condition.

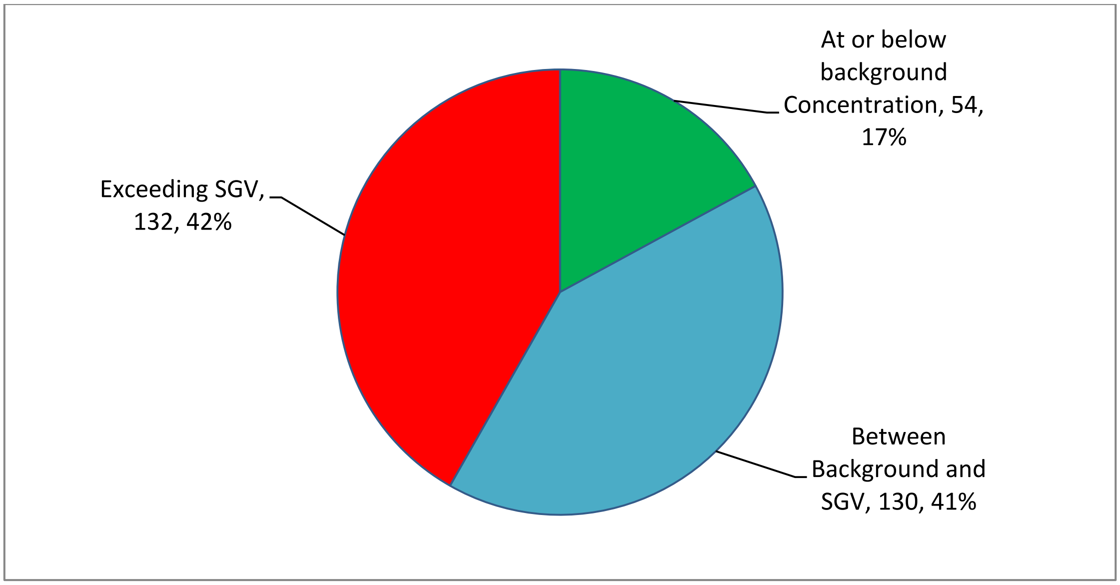

Figure 4.1 Distribution of soil lead concentration as a function of background and soil guideline values. (Landcare Research, 2015; Ministry for the Environment, 2011a).

The predicted background soil lead concentrations (95th percentile) for the sample locations have been defined by Landcare research (2015) and range from 25.8mg kg^{-1} to 46.7mg kg^{-1}. The higher background lead concentration of 46.7mg kg^{-1} was adopted as a conservative background concentration for analysis and interpretation of the results of the current study. Of all samples taken, 17.1% (54) samples were at or below expected background concentrations, 41.1% (130) were between background concentrations and the soil guideline value of 210mg kg^{-1}, and 41.8% (132) of all samples exceeded the soil guideline value (Figure 4.1) (Ministry for the Environment, 2011a). The large proportion (82.91%) of measured soil lead concentrations in excess of both the adopted background concentration of 46.7mg kg^{-1} (Landcare Research, 2015) and the soil guideline value of 210mg kg^{-1} (Ministry for the Environment, 2011a) suggests anthropogenic contamination of soils at the majority of residential properties investigated.

The following sections will discuss the trends and results from individual properties and the relationship between total soil lead and measured variables; age, construction type, paint condition, traffic volume, sample location and soil type.

4.2.2 Total Lead Concentrations by Property

Thirty four properties were sampled with mean soil lead concentrations ranging between 20.4mg kg^{-1} to 3428.1mg kg^{-1} and median values ranging between 16.3mg kg^{-1} and 3521.6mg kg^{-1} (Figure 4.2b). Of all properties sampled; 11.8% (4) had mean and median values lower than the predicted background soil lead concentration, 88.2% had mean and median values above the predicted background soil lead concentration, 50% of properties had a mean soil lead concentrations exceeding the soil guideline value while only 41.2% of properties had a median soil lead concentrations exceeding the soil guideline value (Figure 4.2a). Out of the 34 properties, 32.4% (11) had no samples where the measured soil lead concentration exceeded the SGV. For 58.8% (20) of properties, at least one sample exceeded the soil guideline value. 41.2% (14) of the sample properties had more than 50% of the samples exceed the SGV. For the remaining 11.8% (4) of properties, every sample taken was in exceedance of the SGV (Figure 4.2b).

(a)

a.

(b)

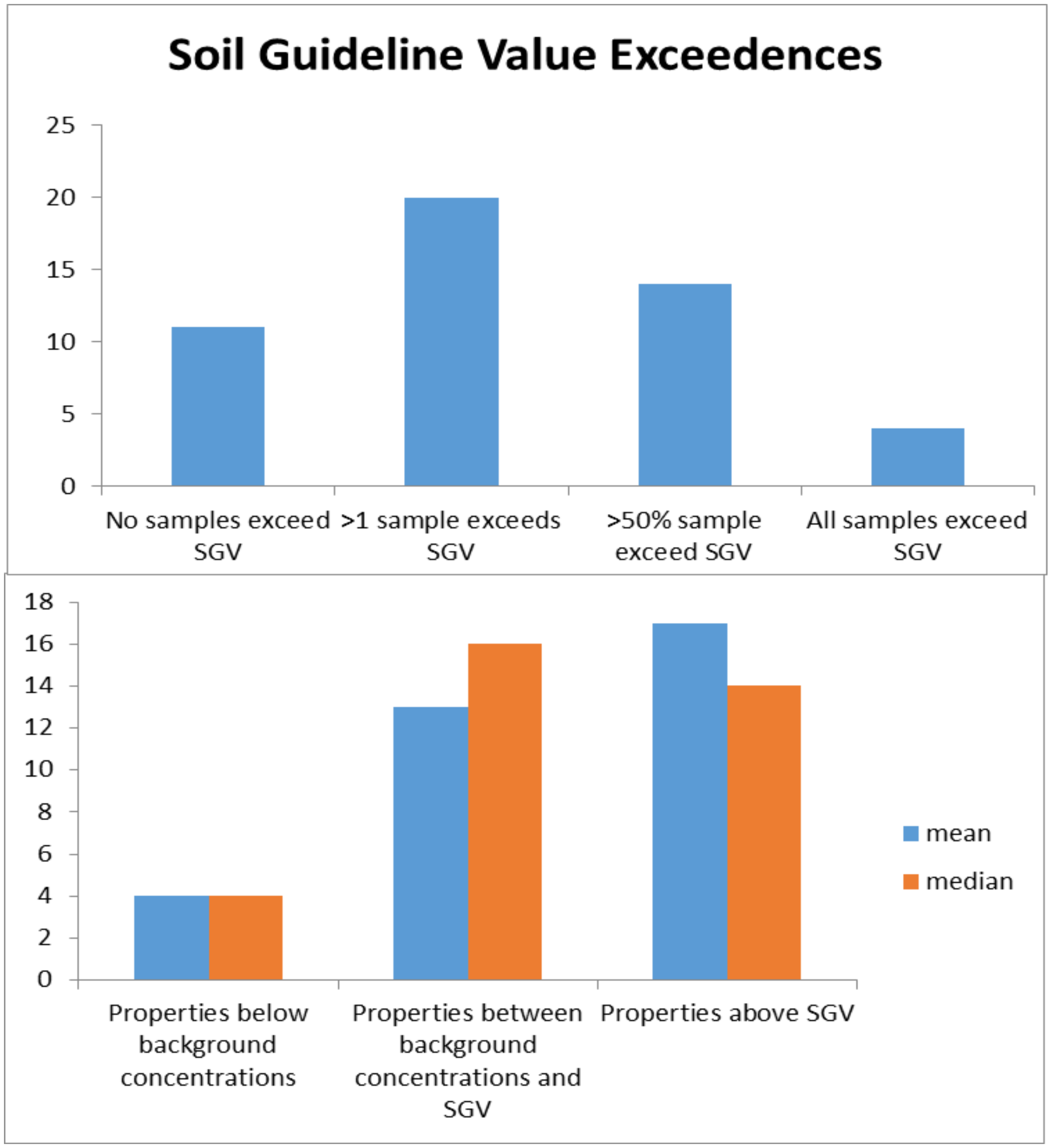

Figure 4.2 (a) Number of properties with samples exceeding the Ministry for the Environment's (2011a) soil guideline value (SGV) of 210mg kg^{-1}. (b) Number of properties below background estimated (95th percentile) soil lead concentrations (Landcare Research, 2015), between background and SGV and exceeding the Ministry for the Environments (2011a) SGV of 210mg kg^{-1}.

Figure 4.3 presents the range of soil lead values recorded across all properties and demonstrates the variability of soil lead concentrations across the sample population. Properties AG, H, I, M, S and Y had mean concentrations significantly elevated above the soil guideline values (Ministry for the Environment, 2011a). Properties with the highest soil lead concentrations exhibited greater variability between samples when compared to properties with lower mean soil lead concentrations (Figure 4.3). This is reflected by higher standard deviations and standard errors in properties with high mean soil lead concentrations (Table 4.1). The greater variability exhibited by properties with high soil lead concentrations could be due to the distribution of soil lead around homes.

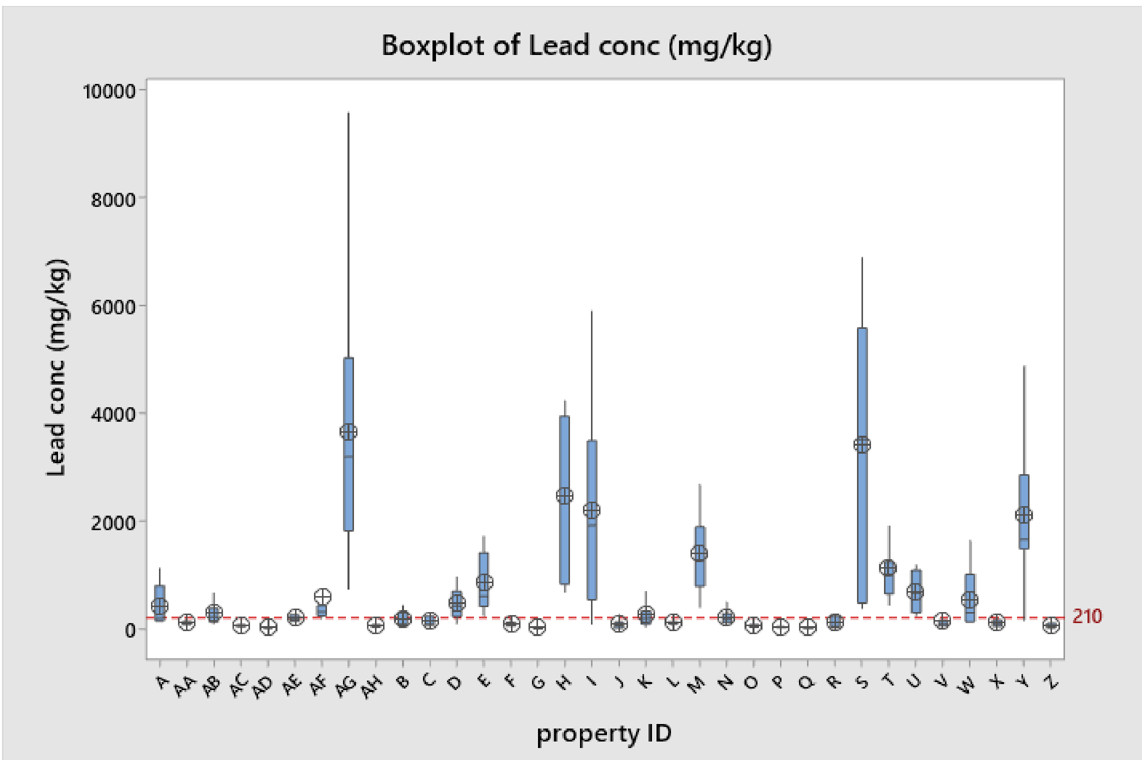

Figure 4.3 Box and whisker plot of soil lead concentrations in mg kg^{-1} by sampling location with mean value denoted by an x. dotted line represents the 210 mg kg^{-1} SGV for lead.

Table 4.1 Statistical measures of total soil lead concentrations for each property sampled. SGV refers to the soil contaminant standard of 210mg kg^{-1} as defined by the Ministry for the Environment (2011a) for residential properties with 10% produce.

Property	N	Mean (mg kg^{-1})	Geometric mean (mg kg^{-1})	Median (mg kg^{-1})	Minimum (mg kg^{-1})	Maximum (mg kg^{-1})	Standard deviation	Standard error	Range (mg kg^{-1})	Samples above SGV	Samples above SGV (%)
All Sites	***316***	***642.7***	***207.6***	***158.8***	***11.5***	***9571.0***	***1281.2***	***50.5***	***19.6-9571.0***	***132***	***41.77***
A	12	383.6	271.8	204.0	89.5	1134.5	356.9	103.0	89.5-1134.5	5	41.67%
B	10	168.2	126.3	94.8	49.0	437.0	137.0	43.3	49-437	3	30.00%
C	11	174.4	137.5	98.0	79.5	515.5	147.3	44.4	79.5-515.5	3	27.27%
D	10	439.7	341.8	398.8	94.0	962.5	289.6	91.6	94.0-962.5	7	70.00%
E	10	868.0	712.8	618.8	256.5	1717.5	549.0	173.6	256.5-1717.5	10	100.00%
F	12	103.3	94.8	97.5	44.5	204.5	45.0	13.0	445-20.5	0	0.00%
G	8	20.4	18.9	16.3	11.5	37.0	9.3	3.3	11.5-37.0	0	0.00%
H	7	2469.7	1979.2	2477.9	690.9	4238.0	1539.5	581.9	690.9-4238.0	7	100.00%
I	10	2207.4	1394.6	1923.9	107.1	5889.8	1809.9	572.3	107.1-5889.8	9	90.00%
J	8	96.9	71.1	77.2	22.8	271.7	83.3	29.5	22.8-271.7	1	12.50%
K	8	381.9	246.2	220.3	51.1	1232.7	397.9	140.7	51.1-1232.7	5	62.50%
L	9	112.2	108.2	103.1	61.3	160.2	31.5	10.5	60.3-160.2	0	0.00%
M	9	1238.7	808.8	914.9	35.6	2677.9	841.8	280.6	35.6-2677.9	8	88.89%
N	7	221.9	193.9	184.8	99.6	501.4	137.3	51.9	99.6-501.4	2	28.57%
O	10	70.2	58.8	48.8	28.5	201.3	52.3	16.5	28.5-201.3	0	0.00%
P	9	44.9	43.8	45.0	31.7	62.3	10.2	3.4	31.7-62.3	0	0.00%
Q	10	27.7	27.2	26.0	20.9	37.8	5.7	1.8	20.9-37.8	0	0.00%
R	8	109.4	77.1	49.3	26.7	249.0	98.2	34.7	26.7-249.0	2	25.00%
S	10	3428.1	2200.6	3521.6	390.6	6887.4	2526.7	799.0	390.6-6887.4	10	100.00%
T	12	1030.4	727.5	999.9	21.3	2363.5	633.3	182.8	21.3-2363.5	11	91.67%
U	9	413.1	203.4	255.6	34.8	1197.3	441.9	147.3	34.8-1197.3	5	55.56%
V	8	145.3	119.1	113.1	65.0	395.2	110.9	39.2	65.0-395.2	1	12.50%
W	11	546.6	352.0	312.0	128.7	1637.3	526.2	158.7	128.7-1637.3	6	54.55%
X	10	183.5	121.9	105.6	44.4	823.3	231.6	73.2	44.4-823.3	1	10.00%
Y	10	1920.0	1222.8	1658.2	91.6	4865.7	1404.5	444.2	91.6-4865.7	8	80.00%
Z	7	68.0	57.6	49.3	27.3	127.9	41.8	15.8	27.3-127.9	0	0.00%
AA	9	122.3	117.1	119.1	73.7	200.5	39.3	13.1	73.7-200.5	0	0.00%
AB	7	287.6	243.4	228.3	109.3	664.5	190.7	72.1	109.4-664.5	4	57.14%
AC	9	72.2	66.9	76.2	24.3	104.0	25.4	8.5	24.3-104.0	0	0.00%
AD	9	31.9	30.5	30.0	19.6	49.4	10.1	3.4	19.6-49.4	0	0.00%
AE	7	162.6	129.3	183.2	30.2	287.9	95.8	36.2	30.3-287.9	2	28.57%
AF	11	593.3	390.4	324.7	199.5	3234.6	880.8	265.6	199.5-3234	10	90.91%
AG	12	3644.6	3001.6	3201.4	754.7	9571.0	2363.8	682.4	754.7-9570	12	100.00%
AH	7	65.5	59.7	50.2	28.6	110.9	29.7	11.2	28.6-110.9	0	0.00%

4.2.2 Property Age

Property age and soil lead concentrations were shown to be significantly correlated. Older homes had significantly higher soil lead concentrations ($P<0.0005$) (Figure 4.4). The properties sampled ranged in age of first construction from 1901 to 1982; properties built more recently than 1982 were not included in this research due to New Zealand regulation removing the majority of lead from paint by the beginning of the 1980's (Ministry of Health, 2012). For data analysis, the sample properties were grouped into decades of first construction. Only one property ($n=9$[1]) was from the 1980 decade and has been included in the 1970 or older group to allow for meaningful analysis. The mean soil lead concentrations calculated as a function of decade built ranged from 3286mg kg $^{-1}$ to 60mg kg $^{-1}$ (Figure 4.5(b)). Properties first constructed in the 1960's and 1970's onwards had mean soil lead concentrations below the 210mg kg^{-1} SGV for lead. Properties constructed in the 1940's and 1950's had mean concentrations exceeding the SGV but had 95% confidence intervals of 2-884mg kg^{-1} and 150-605mg kg^{-1} respectively. The range of the confidence intervals shows that there is variability in the sample population which increases in properties with older dates of first construction.

[1] n=9 reports 9 soil samples collected from this one property

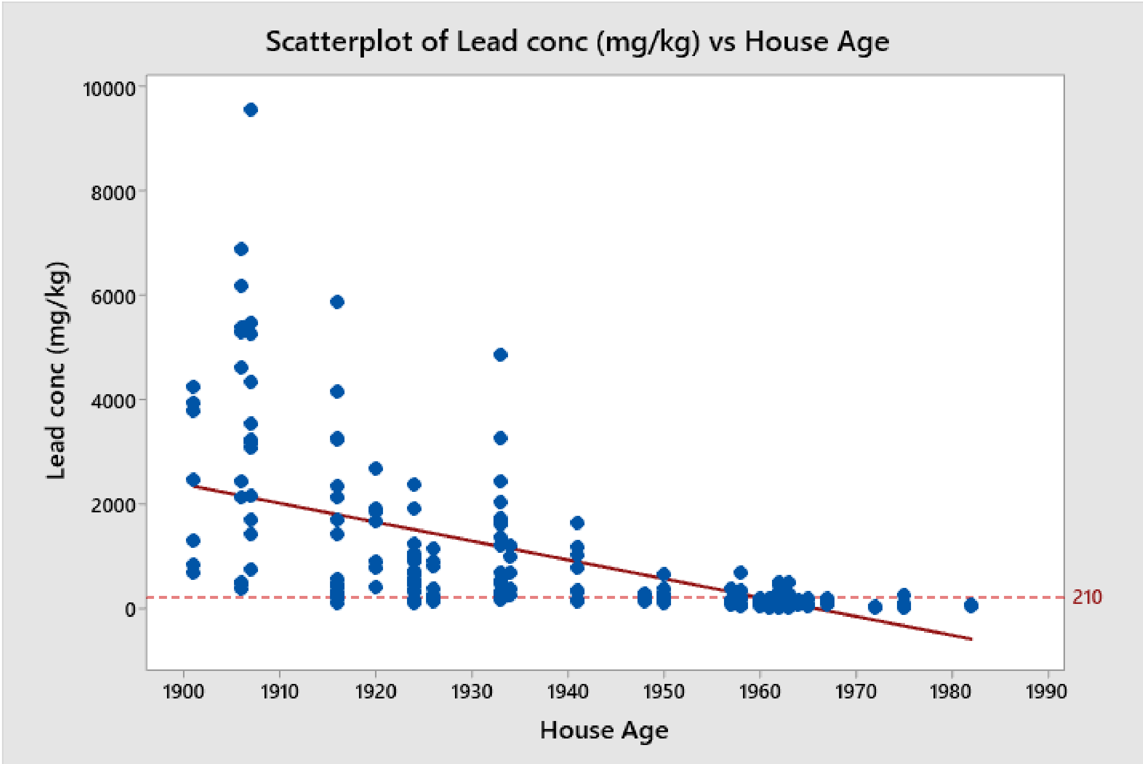

Figure 4.4 Plot of individual sample soil lead concentrations in mg kg^{-1} by age of property.

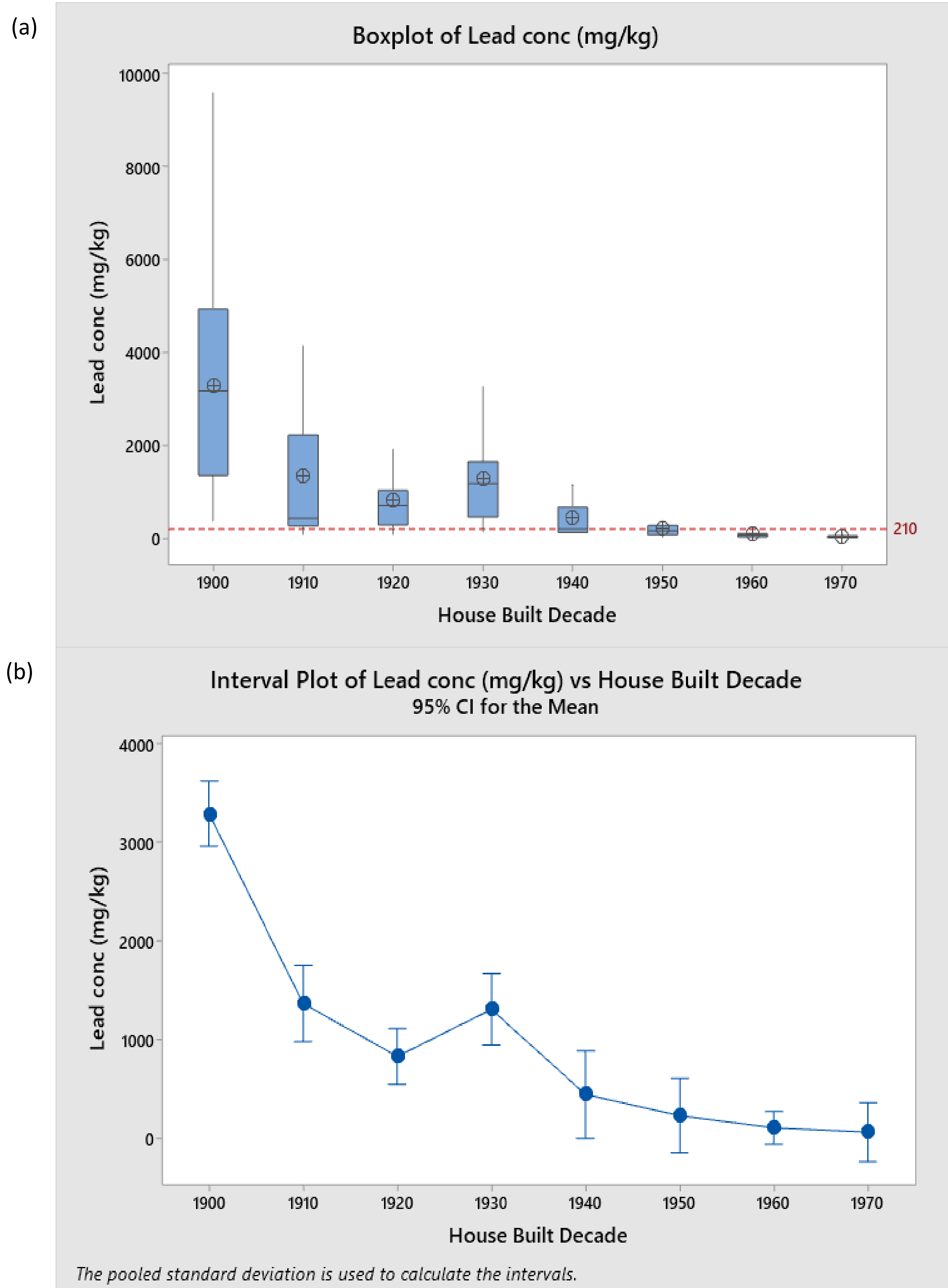

Figure 4.5 (a) Box and whisker plot of soil lead concentrations in mg kg^{-1} by age of house. House ages have been grouped into decade of first construction for analysis, dotted line represents the 210mg kg^{-1} SGV for lead. (b) Plot of mean soil lead concentrations in mg kg^{-1} by age of house. House ages have been grouped into decade of first construction for analysis.

All properties constructed in the 1930's and earlier had mean concentrations exceeding the SGV but again had greater variability in lead concentrations than younger properties (95% confidence). Properties were also grouped with date of construction before 1945 and those after 1945. The first construction date of 1945 was selected as an investigation level because of the removal of white lead from domestic paints was regulated in 1945 (Ministry of Health, 2012). White lead was a major additive in lead-based paint prior to 1945, comprising up to 50% of the paint by weight (Jordan & Hogan, 1975; Ministry of Health, 2012). Figure 4.6 is a box and whisker plot of the soil lead concentrations for properties first constructed before 1945 and after 1945. Samples collected from houses constructed before 1945 (n=178) were found to have significantly higher soil lead concentrations than those built after 1945 (n=124) ($P<0.005$). The mean soil lead concentration in samples collected from homes built before 1945 was 1560mg kg^{-1} while it was only 114mg kg^{-1} in homes built after 1945.

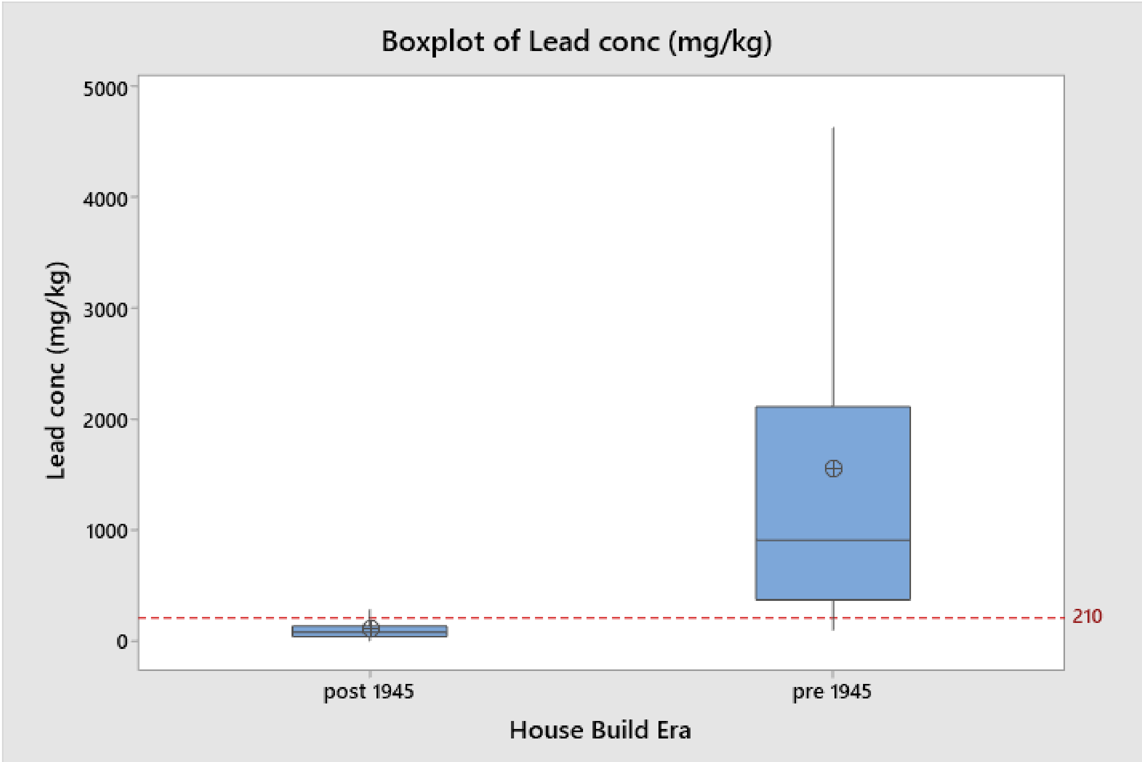

Figure 4.6 Box and whisker plot of soil lead concentrations in homes constructed before and after 1945. Dotted line represents the 210mg kg^{-1} SGV for lead.

4.2.3 Construction Type

Construction type was recorded for all properties sampled which were categorised into four groups based on the dominant exterior cladding; weatherboard, stucco, brick, or brick with wooden trim. There was no statistical difference in soil lead concentrations found between brick, stucco and brick with wooden trim properties (Figure 4.7). There was a significant difference in soil lead concentrations between samples collected from weatherboard properties (n=163) when compared to those collected from all other construction types (P<0.005). Weatherboard properties had a mean soil lead concentration of 1167mg kg^{-1}, well in excess of the 210mg kg^{-1} SGV. Both brick (n=24) and stucco (n=88) properties had mean soil lead concentrations below the SGV of 210mg kg^{-1}.

Brick with wooden trim properties had a mean concentration of 264mg kg^{-1} but had a wide range with a standard deviation of 405mg kg^{-1}. Three properties in the study were brick with wooden trim (n=27) and only one exhibited soil lead concentrations exceeding the SGV. These samples were collected from beneath window frames that had recently had the paint scraped back as part of a renovation[2]. Deposited paint flakes from this renovation works are likely to have contributed to the high soil lead concentrations as the property was first constructed in the 1930s. When these five soil samples are removed from the brick with wooden trim category the mean drops from 264mg kg^{-1} to 97mg kg^{-1} (n=22). Other samples collected from beneath non-renovated window frames on the same property had soil lead concentrations below the SGV indicating that renovation behaviour may influence soil lead concentrations more than weathering alone.

[2] The property owner estimated that the renovation had occurred within the last twelve months, at the time of sampling.

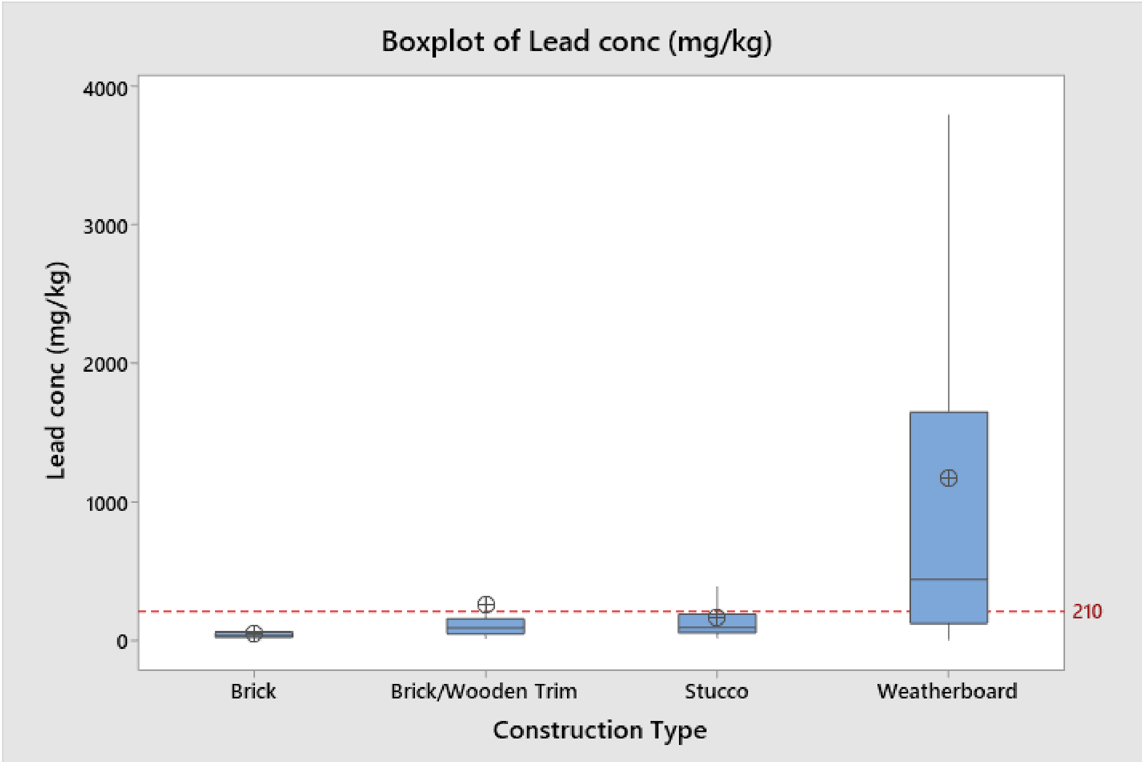

Figure 4.7 Plot of total soil lead concentrations in mg kg^{-1} by construction type (exterior cladding) on the sample property. Dotted line represents the 210mg kg^{-1} SGV for lead.

4.2.4 Paint Condition

Paint condition at each property sampled was visually assessed and recorded during sampling. Each property has been assessed as having either a good, average or poor paint condition. Paint that was flaking or peeling was regarded as in poor condition while paint that had been recently applied or washed was considered in good condition. All properties that were not categorised as good or poor were grouped into the average category. Only one brick home had no paint present at all. The distribution of soil lead concentrations in samples collected from properties of the different categories is presented in Figure 4.8. There was a statistically significant difference in soil lead concentrations in properties with poor paint condition when compared to those with average or good condition paint, or properties without any paint (P<0.005). The mean soil lead concentration for properties with poor paint condition (n=86) was 1449.4mg kg^{-1} which is in excess of the SGV of 210mg kg^{-1}. The mean soil lead concentrations for properties with average (n=119) and good (n=87) paint condition were also in exceedance of the SGV at 590mg kg^{-1} and 214mg kg^{-1} respectively. However, the data had a wide spread with a standard deviation of 1354mg kg^{-1} and 380mg kg^{-1} respectively.

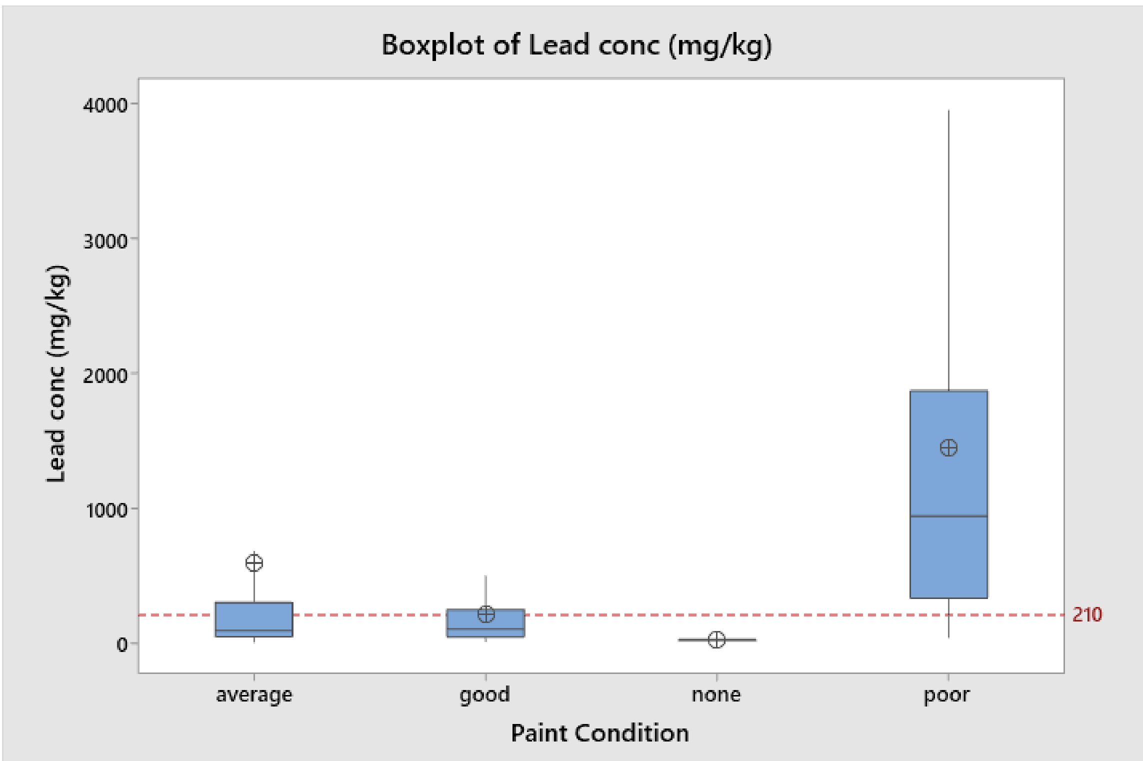

Figure 4.8 Plot of total soil lead concentrations in mg kg^{-1} by condition of the paint on the sample property. Dotted line represents the 210mg kg^{-1} SGV for lead.

4.2.5 Road Classification

The New Zealand Transport Agency (2019) has categorised New Zealand roads based on typical daily traffic, use by heavy commercial vehicles, connectivity and freight using the One Network Road Classification system (ONRC). The ONRC specifies six main road classifications; national, regional, arterial, primary collector, secondary collector and access and a sub-classification of low volume (access) in descending order of traffic density (New Zealand Transport Agency, 2019). Sample properties were predominantly adjacent to access or low volume roads (n=216) which are graded for residential access only. No sample properties were located adjacent to national category roads and only one was adjacent to a regional road. The current study found that there was a statistically significant difference between several of the road classifications and soil lead concentrations ($P<0.005$). Primary collector roads were found to have significantly higher soil lead concentrations than all other categories (Figure 4.9). Three properties were adjacent to primary collector roads (n=33) and were all weatherboard properties first constructed <1920, with average to poor paint condition. Properties within the arterial classification group also had the same variables as primary collector properties. This indicates that age, construction and paint condition may be influencing the relationship shown in the current study more than traffic volumes/density. If traffic volume/density were to have a significant influence on soil lead concentrations then we would expect to see mean soil lead concentrations increasing with traffic density. Instead we see arterial and regional roads which have higher traffic volumes exhibit lower soil lead concentrations in adjacent properties (Figure 4.9). Road traffic volumes/density do not appear to be influencing soil lead concentrations on the sample properties, this is explored further in Chapter Five using case study properties to investigate the spatial distribution of lead across residential properties.

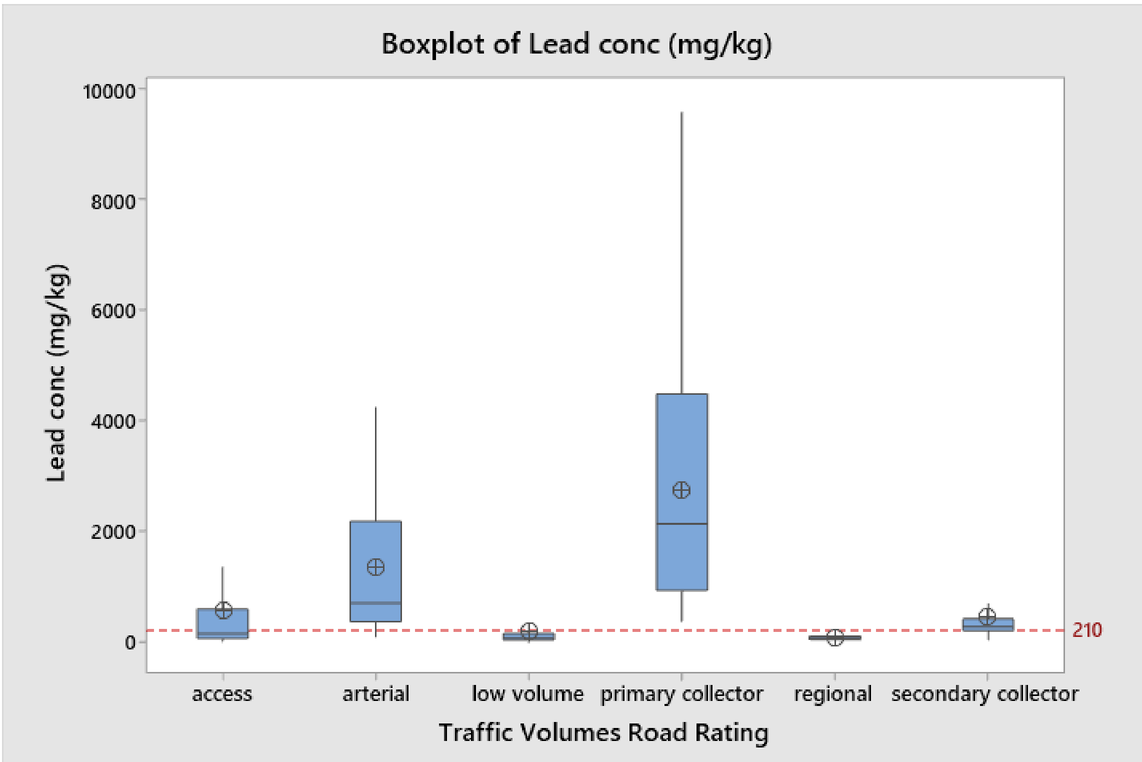

Figure 4.9 Plot of total soil lead concentrations in mg kg^{-1} by NZTA classification of adjacent road at each sample location. Dotted line represents the 210mg kg^{-1} SGV for lead.

4.2.6 Other Recorded Variables

Other variables between the properties recorded at the time of sampling were basic soil description (Figure 4.10), built features adjacent to the sampling location (Figure 4.11), and sampling location (Figure 4.12). The soil at each sampling location was described as organic matter, gravel or clay dominated when sampled. There was no significant relationship found between soil lead concentrations and soil description (P>0.05). Mean soil lead concentrations were similar in all soil types ranging from 634-857mg kg^{-1} (Figure 4.10).

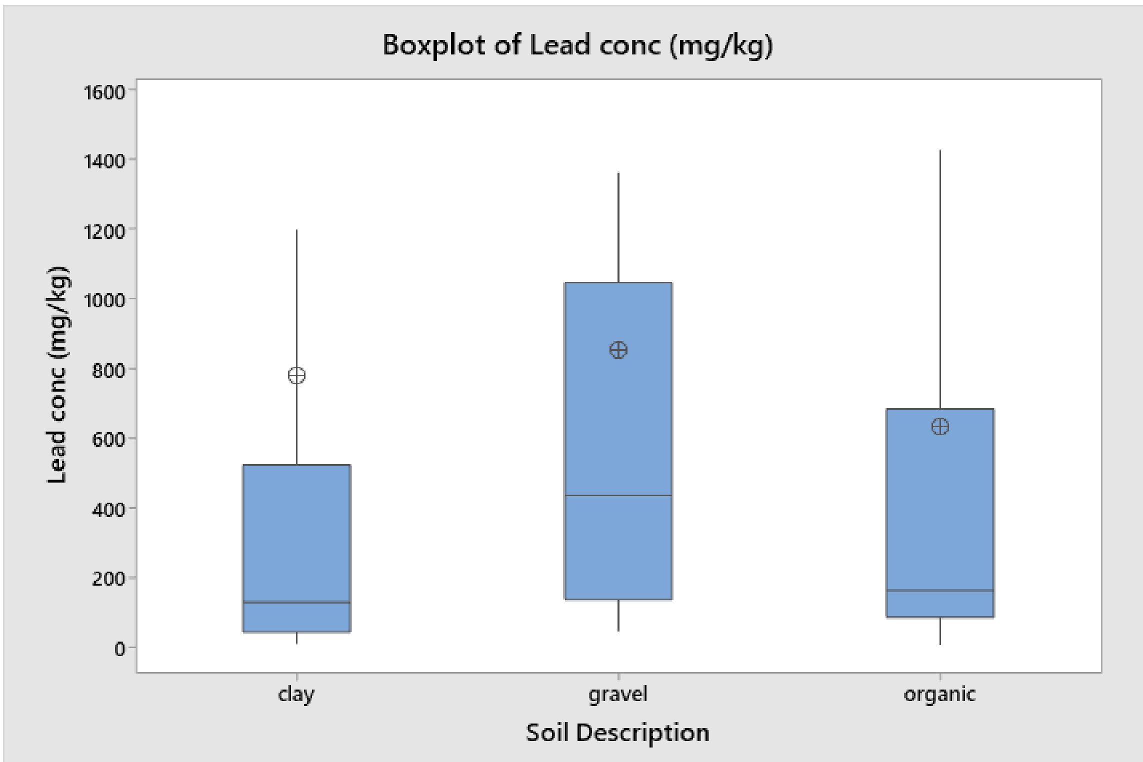

Figure 4.10 Plot of total soil lead concentrations in mg kg^{-1} soil type at each sample location.

Built features adjacent to sampling locations were also recorded and the different categories are displayed in Figure 4.11. All features with the exceptions of 'driveway' and 'none' are painted structures. There was no statistically significant difference between soil lead concentrations and any adjacent feature in particular. However, there were higher concentrations found near entrance areas and windowframes/driveways (Figure 4.11)

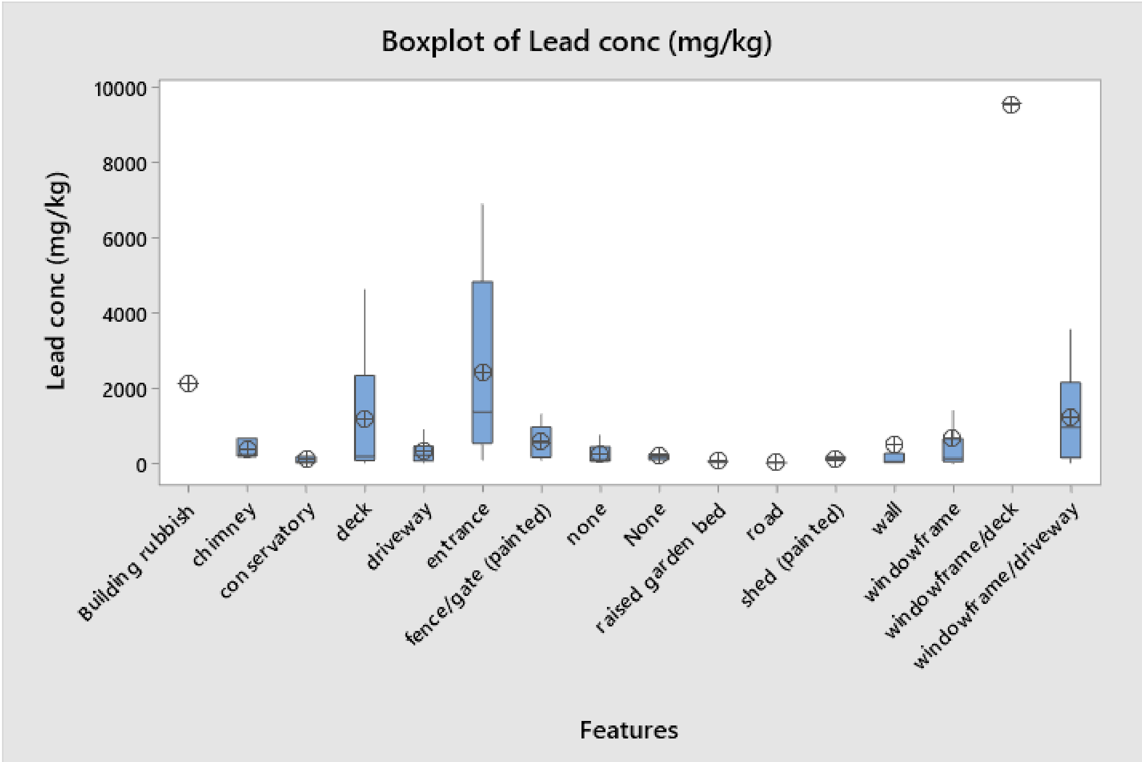

Figure 4.11 Plot of total soil lead concentrations in mg kg^{-1} by residential structural feature at each sample location.

Soil sampling location was recorded at the time of sampling as one of the following categories; Bare soil, garden, gravel, lawn, raised garden or road verge (Figure 4.12). There was no statistically significant difference in soil lead concentrations between the different sampling locations ($p>0.05$). The mean soil lead concentrations range from 320mg kg^{-1} to 961mg kg^{-1} for the different sample location categories. One sample (road verge) was collected from the road verge of a regional road and when analysed recorded a low soil lead concentration.

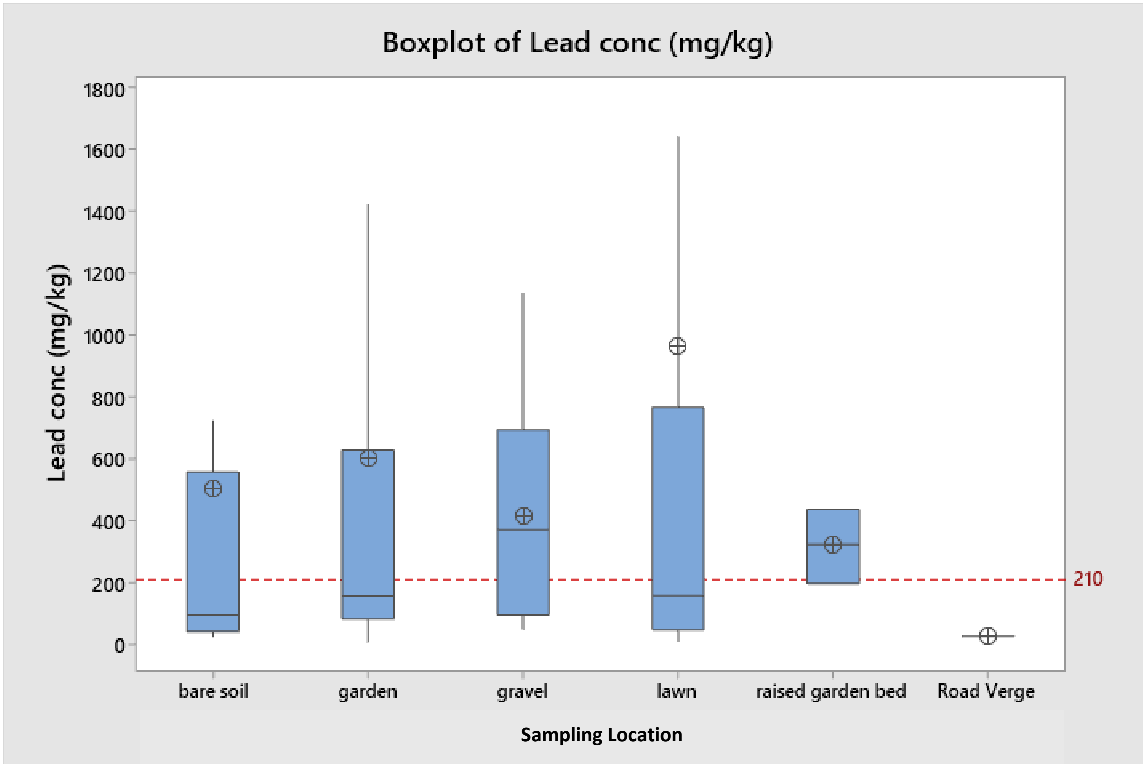

Figure 4.12 Plot of total soil lead concentrations in mg kg^{-1} by sampling location. Dotted line represents the 210 mg kg^{-1} SGV for lead.

4.3 Discussion of Initial Investigation Results

The results of this initial investigation demonstrate that lead-based paint is a significant contributor to lead concentrations in urban and suburban residential soils of Palmerston North City. Research in other countries such as Australia (Kandic et al, 2019; Rouillon et al, 2017) and the United States (Clark & Knudsen, 2014; Clarke et al, 2015; Codling, 2013; Jacobs et al, 2002; United States Environmental Protection Agency, 1995) has shown that lead-based paint on residential properties is a major contributor to soil lead concentrations. Property characteristics have been shown to significantly influence soil lead concentrations in other studies such as property age (Kandic et al, 2019), construction type (Jordan & Hogan, 1975; Clarke et al, 2015), paint condition (Clark & Knudsen, 2014) and distance to roads (Laidlaw et al, 2018). Soil lead concentrations were found to be elevated above background concentrations on 88% of properties sampled (n=34) (Landcare research, 2015). Only 12% of properties sampled had soil lead concentrations consistent with predicted background lead concentrations (Figure 4.1). Of the properties sampled, 50% had mean soil lead concentrations above the SGV of 210mg kg^{-1} (42% of all samples) (Ministry for the Environment, 2011a). The proportion of samples and sampled properties in exceedance of the lead SGV is higher than that reported in recent studies (Kandic et al, 2019; Rouillon et al, 2017). However, this may be because of the focus of these studies on lead concentrations within garden soils instead of samples near the house curtilage. From a review of the literature, two studies by Jordan and Hogan (1975) and Clark and Knudsen (2014) examined the effects of lead-based paint on a comparable small urban residential neighbourhood. In Clark and Knudsen's (2014) study of Appleton, Wisconsin, they found that two thirds of properties sampled exceeded the relevant soil lead guideline value of 400mg kg^{-1}. Jordan and Hogan (1975) found that 38% of samples (n=437) from residential properties in Christchurch, New Zealand, exceeded the then SGV of 300mg kg^{-1}. It is important to highlight that the soil guideline value used for Clark and Knudsen's (2014) and Jordan and Hogan (1975) studies were higher than the current New Zealand SGV. Assessing the soil lead concentrations found by Jordan and Hogan (1975) against the current SGV would likely result in a similar number of exceedances to that found in the current study. Another study by Codling (2013) investigated spatial distribution of lead-based paint contamination on two rural properties showing that lead concentrations decreased with depth and distance from the house. Both properties investigated by Codling (2013) had mean soil lead concentrations exceeding the 400mg kg^{-1} SGV. The results of the current study sit in between other reported results most likely due to the location of the sampling along the dripline of properties closer to lead-based paint structures resulting in higher lead concentrations than studies focussing on gardens (Rouillon et al, 2017). It is likely lower than those found by Clark and Knudsen (2014) because of the age of the properties investigated were older (85% built pre 1950) than those in the current study which had an average age first constructed of 1947. The current study has similar soil lead concentrations and spatial variation to that reported by Codling (2013) in an investigation of lead-based paint contamination on rural properties and results reported by Jordan and Hogan (1975).

Soil lead concentration was found to be significantly influenced by property age (Figure 4.4) ($P<0.005$). The properties sampled in the current study ranged in age from 1901 to 1982 which is a similar spread of ages to those sampled in other recent studies (Kandic et al, 2019; Laidlaw et al, 2018; Rouillon et al, 2017). The influence of age of the property on soil lead concentrations found in this study is consistent to that reported by other studies on residential properties (Clark & Knudsen, 2014; Clarke et al, 2015; Jordan & Hogan, 1975; Kandic et al, 2019; Rouillon et al 2017). This study also found that properties could be divided into two distinct groups based on the soil lead concentrations, those built before 1945 and those built after (Figure 4.6). In 1945 New Zealand regulated lead additives in paint and banned the use of white lead in paints intended for residential use

(Jordan & Hogan, 1975; Ministry of Health, 2012). White lead prior to 1945 was not limited and had been present in domestic paints in amounts up to 50% by weight (Fergusson, 1986; Ministry of Health, 2012). The removal of white lead from domestic paints may explain the significant difference ($P<0.005$) found by the current study in soil lead concentrations between homes built before and after 1945. This result is the same as that found in Christchurch by Jordan and Hogan (1975) who found that there was limited soil lead exceeding the SGV in properties built from 1950 onwards. This significant difference in soil lead concentration between the two age groups provides evidence that the lead found by this study is predominantly from lead-based paints instead of other sources.

Construction type in the current study refers to the dominant exterior wall construction material. The current study found a statistically significant difference ($P<0.005$) between construction types, with weatherboard clad homes exhibiting significantly higher soil lead concentrations than all other construction types. This relationship has been shown in previous studies by Kandic et al (2019) in Melbourne, Clarke et al (2015) in Los Angeles, and Jordan and Hogan (1975) with brick homes exhibiting significantly lower soil lead concentrations than weatherboard homes. A study by Kim and Fergusson (1993) in Christchurch New Zealand showed that lead concentrations in house dust in brick clad homes were significantly lower than those found in weatherboard homes indicating that this trend may have an effect on lead exposure pathways for occupants. The 'brick' and 'brick with wooden trim' properties sampled in this study (n=6) were young, relative to weatherboard properties with an average age of 1962 compared to an average age of

1937 (n=19) for weatherboard properties. The statistical difference in soil lead concentrations found between construction types is predominantly due to weatherboard properties having more painted surface than other construction types. It is also likely to be influenced by the age of the property which was found to be a significant factor in soil lead concentration as older brick homes may have wooden trim or foundation skirting that could have been painted with lead-based paint (United States Environmental Protection Agency, 2019b). The results of the current study showed that property owner behaviour during renovations or similar activities can significantly affect the soil lead concentrations. One of the brick with wooden trim properties sampled had recently undergone stripping back of the window trim. There was obvious paint flakes on and in the soil beneath the area of renovation and samples collected from these areas had lead concentrations in excess of 1000mg kg^{-1} while other locations (beneath wooden window frames) where renovation had not been undertaken exhibited lead concentrations consistent with predicted background concentrations (Landcare Research, 2015). So even on brick houses, there is still a risk of isolated lead hotspots associated with painted window frames and property owner behaviour such as renovating or repainting can significantly influence soil lead concentrations. This finding is consistent with previous studies (Francek et al, 1994; Jacobs et al, 2002; Ministry of Health, 2012). However, it is sensible to conclude that properties with a larger painted area such as weatherboard clad homes would exhibit a greater impact on soil lead concentrations from poor renovation techniques when compared to brick or brick and wooden trim properties with less painted area and therefore less lead-based paint.

There was a significant difference ($P<0.005$) in lead concentrations found between soil samples collected from properties and structures with poor paint and those with average or good paint condition (Figure 4.8). This finding is consistent with other studies (Clark & Knudsen, 2014; Francek et al, 1994; Jacobs et al, 2002; Laidlaw et al, 2018; United States Environmental Protection Agency, 1995) and adds to the evidence that lead-based paint is the dominant contributor to soil lead concentrations on the properties investigated in the current study. Sampled properties with poor paint condition were all built prior to 1950 so it is also likely that the age of the properties may also be influencing the correlation between paint condition and lead concentrations. Properties with good or average paint condition that had samples exceeding the lead SGV could largely be categorised as older weatherboard homes indicating that property age is more influential on soil lead concentrations than paint condition because of the cumulative effects of paint deterioration or removal over time. However, the lead concentrations are likely to be significantly altered depending on the behaviour of the person undertaking renovation or maintenance on properties with lead-based paint. DIY renovators may not be aware of the appropriate precautions to take and standards between contractors are likely to vary.

An important finding to discuss is the influence of traffic volume on soil lead concentrations. For the purposes of this study traffic volume or density and therefore relative levels of emissions of roads adjacent to sample properties has been defined using New Zealand Transport Agency ONCR classification (New Zealand Transport Agency, 2019). The current study found that there was a significant difference ($P<0.005$) between several of the road classifications and soil lead concentrations. In particular, properties located on primary collector roads were found to have statistically higher soil lead concentrations than all other road classifications (Figure 4.9). Properties adjacent to arterial roads were found to have significantly higher soil lead concentrations than access, low volume and secondary collector roads. It is not clear whether traffic volume is having an actual influence on soil lead levels as all properties adjacent to both primary collectors and arterial roads were weatherboard homes first constructed earlier than 1930. Recent studies by Clarke et al (2015) and Laidlaw et al (2018) both showed that soil lead levels decreased away from roads and concentrations were higher near larger or busier roads. The relationship between lead in soils and traffic volume will be examined further in the Chapter Five where the influence of different road categories is analysed and discussed in more detail.

The current study found no significant relationships between soil lead concentrations and other measured variable such as soil type (Figure 4.10), painted features (4.11) or sampling location (Figure 4.12). The effect of soil type is likely to be more important when assessing the bioavailability and actual risk to property owners; the influence of organic matter and soil pH on bioavailability has been described in previous studies (Kandic et al, 2019). The assessment of risk to site occupiers has not been examined as part of this research beyond comparisons to the lead SGV, with the focus instead on the spatial distribution of lead across properties. The implications of the results discussed here and in Chapter Five will be discussed in Chapter Six to develop recommendations for environmental management and further research. In Chapter Five, a more detailed case study investigation is described which was undertaken at three properties selected from the initial investigation.

5.0 Case Study Investigation

5.1 Introduction

The case study investigation in this chapter presents a comprehensive, property-scale investigation into the vertical and lateral distribution of soil lead concentrations at three lead-impacted residential properties within the regional New Zealand urban area of Palmerston North City. The current study represents a more comprehensive investigation than previous New Zealand studies, with three properties systematically investigated with a greater sample density (n=339) than in any study previously conducted to provide a high resolution pattern of soil lead concentrations.

5.1.1 Aims

A case study was conducted to delineate the profile and spatial variation of lead concentration in soil across three residential properties that had previously shown elevated soil lead concentrations (Chapter 4). It is hypothesised that soil lead concentrations will be higher in the topsoil (0-10cm) than in samples collected from the subsoil (10-20cm). It is also hypothesised that soil lead concentrations will decrease with increasing distance from the house or other painted structures.

5.1.2 Selection of Properties and Soil Sampling

To test these hypotheses, three properties (of 34) that showed elevated soil lead concentrations from the initial investigation in Chapter Four were sampled intensively using a systematic 2m grid sampling pattern. The rationale for choosing locations with a record of high lead was that higher soil lead concentrations would provide a stronger pattern of contamination than a less impacted property. The three properties chosen for the case study investigation were properties AG, Y and E. Properties AG, Y and E are all situated on the depositional river soils within the main urban center of Palmerston North City. The soil units underlying all three properties are dominated by the Manawatū series which describes from well to poorly drained silty, sandy loam with moderately acidic topsoil (Cowie, 1977). Soil mapping within the main urban area of Palmerston North has not been investigated in enough detail to allow for further characterisation of the underlying soils at each property. All three properties were selected as they demonstrated the characteristics previously shown to be correlated with elevated soil lead concentrations (Clark & Knudsen, 2014; Jordan & Hogan, 1975; Rouillon et al, 2017). All three properties were weatherboard construction type with average to poor paint condition. Property AG was first constructed in 1900-1910 while properties E and Y were both first constructed during the 1930’s. These properties are representative of the majority of homes first constructed prior to 1945, and belong to the age group from the initial study with the most elevated soil lead concentrations (Statistics New Zealand, 2013). Selecting these properties was targeted to define how soil lead concentrations vary across the properties with these characteristics and within this age bracket. A previous study by Jordan and Hogan (1975) in Christchurch showed that older brick properties did not display significantly elevated soil lead concentrations above the SGV, so further investigation of brick houses in the current study was not undertaken beyond the initial investigation. Previous land use for the three properties was determined from historical mapping available through the Palmerston North City Council, indicating that prior to first construction the land was used for pastoral agriculture. This is consistent with the dominant land use for the district at the time (Cowie, 1977). It is considered unlikely that the previous land uses would have resulted in the elevated soil lead concentrations seen in the initial investigation. To further investigate the case study properties, a systematic 2m x 2m grid was used. Samples were collected from each 2m grid location from the top soil 0-10cm and the sub soil 10-20cm. Variables including distance to nearest painted structure and distance to road from each sample point were investigated to determine any relative influence from sources of environmental lead associated with vehicle emissions and paint.

5.1.3 Statistical Analysis

Descriptive statistics for samples collected (n=339) from individual properties and from all properties combined was calculated using Minitab19 software. Significance testing and graphs of relationships between soil lead concentrations and other recorded variables was completed using Minitab19 software. One-way ANOVA tests were used to identify significant differences in soil lead concentrations between properties and the different variables presented and discussed in this chapter. The interpolation surface of soil lead concentrations at each depth was undertaken using an inverse distance weighted (IDW) function on ArcGIS software similar to that undertaken by other studies (Clark & Knudsen, 2014; Turnbull et al, 2019). The interpolated surface is presented for both sample depths on each property using a minimum of 40 points within a 50m search radius. The surface was displayed using twenty concentration classes at 50mg kg^{-1} increments.

5.2 Combined Results

5.2.1 Soil Lead Concentration

The mean soil lead concentrations for the three investigated properties were 245.7mg kg^{-1} (E), 308.3mg kg^{-1} (Y) and 841mg kg^{-1} (AG) with the higher mean concentration found at the oldest property. All properties had a mean soil lead concentration in exceedance of the lead soil guideline value of 210mg kg^{-1} for residential properties with 10% produce consumption (Figure 5.1) (Ministry for the Environment, 2011a). The mean soil lead concentration for each property was significantly lower than the mean soil lead concentrations found in the initial investigation on the same properties. Median soil lead concentrations were approximately half the mean concentration suggesting strongly skewed data; only the median soil lead concentration for property AG was above the SGV (Table 5.1). There was a statistically significant difference ($P<0.0005$) in the mean soil lead concentrations between property AG and the other two properties sampled. There was no significant difference in mean soil lead concentrations between property E and Y (Figure 5.1). The differences in soil lead concentration follow from the age of the properties; property AG is older, being first constructed in 1900's while the other two were first constructed in the 1930's. Minimum soil lead concentrations at all three properties were at or below background concentrations for the area (Landcare Research, 2015). All three properties showed elevated soil lead concentrations with 79% of samples collected at property AG exceeding the 210mg kg^{-1} SGV for lead and properties E and Y having 40% and 37% respectively of samples exceeding the SGV (Figure 5.1) (Ministry for the Environment, 2011a).

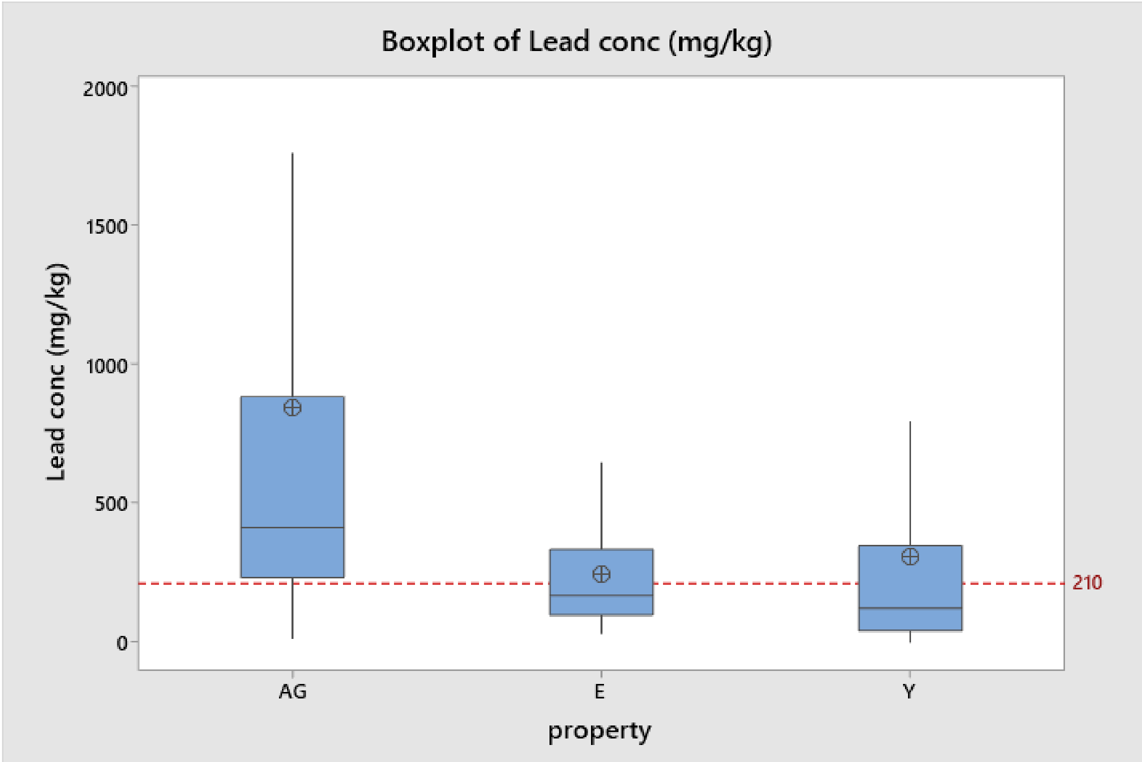

Figure 5.1 Box plot of soil lead concentrations at different properties with mean values denoted by a plus. Dotted line represents the 210 mg kg^{-1} SGV for lead.

5.2.2 Vertical Distribution of Lead

In some locations no sample was able to be collected from the 10-20cm depth due to underlying structures or fill. The descriptive statistics for samples collected from all properties at each depth horizon is presented in Figure 5.2. For all samples collected, the mean soil lead concentration in the 0-10cm depth was 627mg kg^{-1} (n=170) and the mean concentration for the 10-20cm depth was 357mg kg^{-1} (n=166). The difference in concentrations between the two depths was statistically significant ($P<0.007$) with the 0-10cm depth exhibiting greater mean and median soil lead concentrations than samples collected at 10-20cm (Figure 5.2). For all samples combined, both the 0-10cm and 10-

20cm depths had mean soil lead concentrations exceeding the 210mg kg^{-1} SGV for lead (Ministry for the Environment, 2011a). The median value for the 0-10cm horizon also exceeded the SGV while the median value for the 10-20cm horizon was below the SGV (Figure 5.2). The mean soil lead concentration in the 10-20cm horizon at each location was found to be skewed towards higher concentrations by several samples that were taken from highly disturbed gardens where soils were well mixed between the two layers. The range of soil lead concentrations was greater in the 0-10cm horizon than it was in the 10-20cm horizon. The maximum soil lead concentration across all three properties was 7535mg kg^{-1} which was from a sample collected in the 0-10cm horizon adjacent to the oldest house.

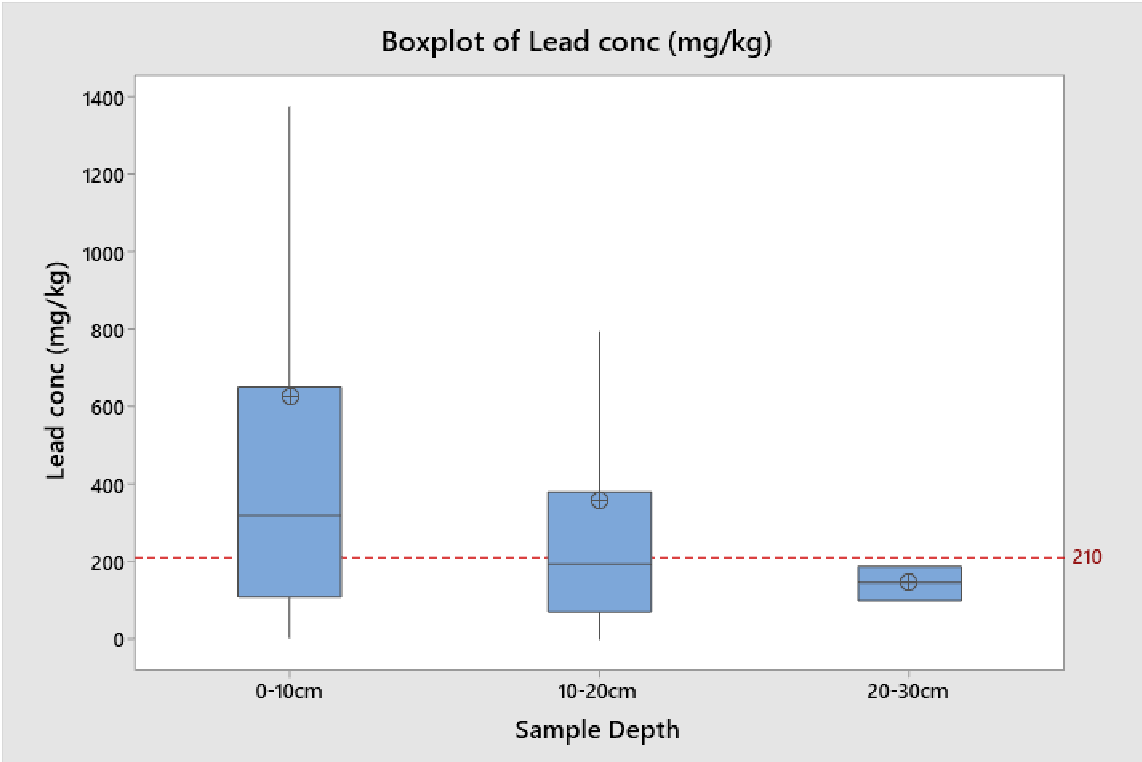

Figure 5.2 Box plot of soil lead concentrations across all properties at varying sample depths with mean value denoted by a plus. Dotted line represents the 210mg kg^{-1} SGV for lead.

There was a clear trend in soil lead concentration between the two depths (Figure 5.3) with samples collected from the 0-10cm horizon comprising 79% of samples with soil lead concentrations of 1000mg kg^{-1} or higher, and 52% of samples with soil lead concentrations between 210-1000mg kg^{-1}. Conversely, 64% of samples with soil lead concentrations below background (<46.6mg kg^{-1}) and 56% of samples with soil lead concentrations between 47mg kg^{-1}-210mg kg^{-1} were collected form the 10-20cm depth (Figure 5.3).

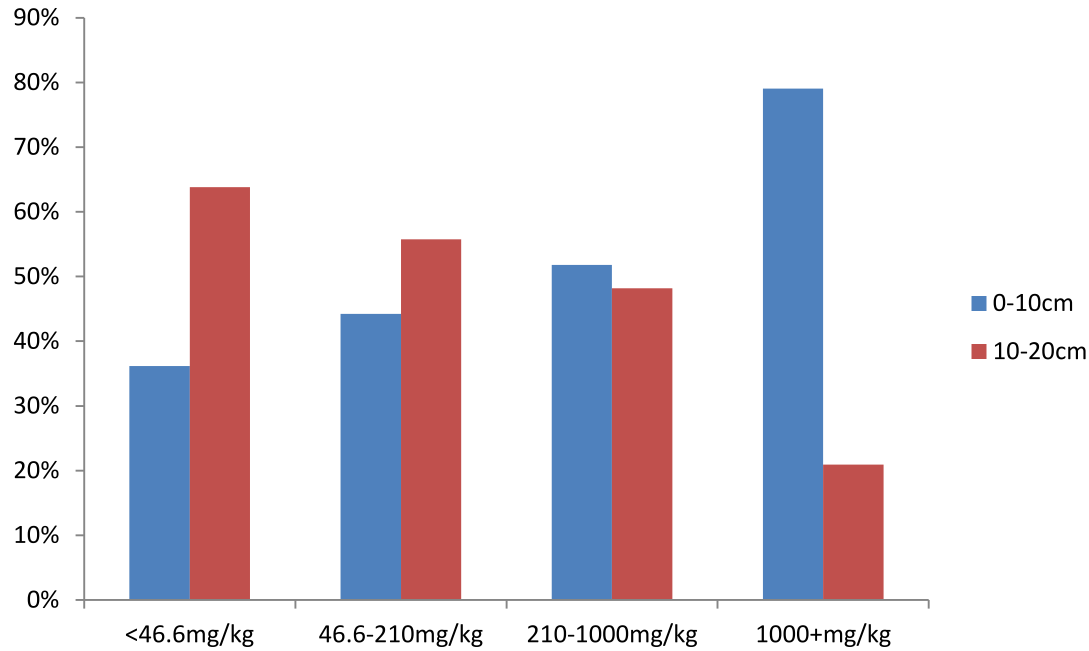

Figure 5.3 Percentage of samples in each soil lead concentration band by sampling depth.

5.2.3 Lateral Distribution of Lead

This study found that there was significant effect of distance from the nearest painted structure and the soil lead concentration (P<0.005). In most cases this was the house, but painted sheds and patios were also recorded as a painted structure. These statistics were calculated using both the 0-10cm and 10-20cm depth ranges combined. The difference between soil lead concentration and distance from painted structures and depth is explored in more detail for each case study property in the following sections. Samples were collected at distances ranging from immediately adjacent (0m) up to 16m away from the nearest painted structure (Figure 5.4).

There was a significant difference in soil lead concentrations ($P<0.005$) between samples collected immediately adjacent (0m) to a painted structure (n=97) and all other distances (n=242). There was no significant difference in soil lead concentrations between any other distances measured in this study indicating that the influence of lead-based paint on soil lead concentration is most significant in the immediate curtilage of the house. However, there was a general trend of soil lead concentrations decreasing with distance from the house (Figure 5.4). There was a 45% reduction in soil lead concentration between samples collected adjacent to the house and those collected 2m away. There was a 28% reduction of soil lead concentration between samples collected at 2m distance and those at 4m distance. Between samples collected at 4m and 6m distance there was a 43% reduction in mean soil lead concentration with greater distance. Further increases in distance from the house showed reductions in mean soil lead concentrations of 10%, 23%, and 25% for samples collected 8m, 10m and 12m respectively from the house. The mean and median concentrations of soil lead for samples collected 0m and 2m from a painted structure both exceeded the 210mg kg^{-1} SGV (Figure 5.4) (Ministry for the Environment, 2011a). For samples collected 4m from a painted structure the mean exceeded the SGV but the median was below. The mean and median values for samples collected 6m or more from a painted structure were all less than the SGV. Background lead concentrations were found in samples at every distance from painted structures except for the 16m range when the single sample taken at both depths was slightly elevated above background (Landcare Research, 2015).

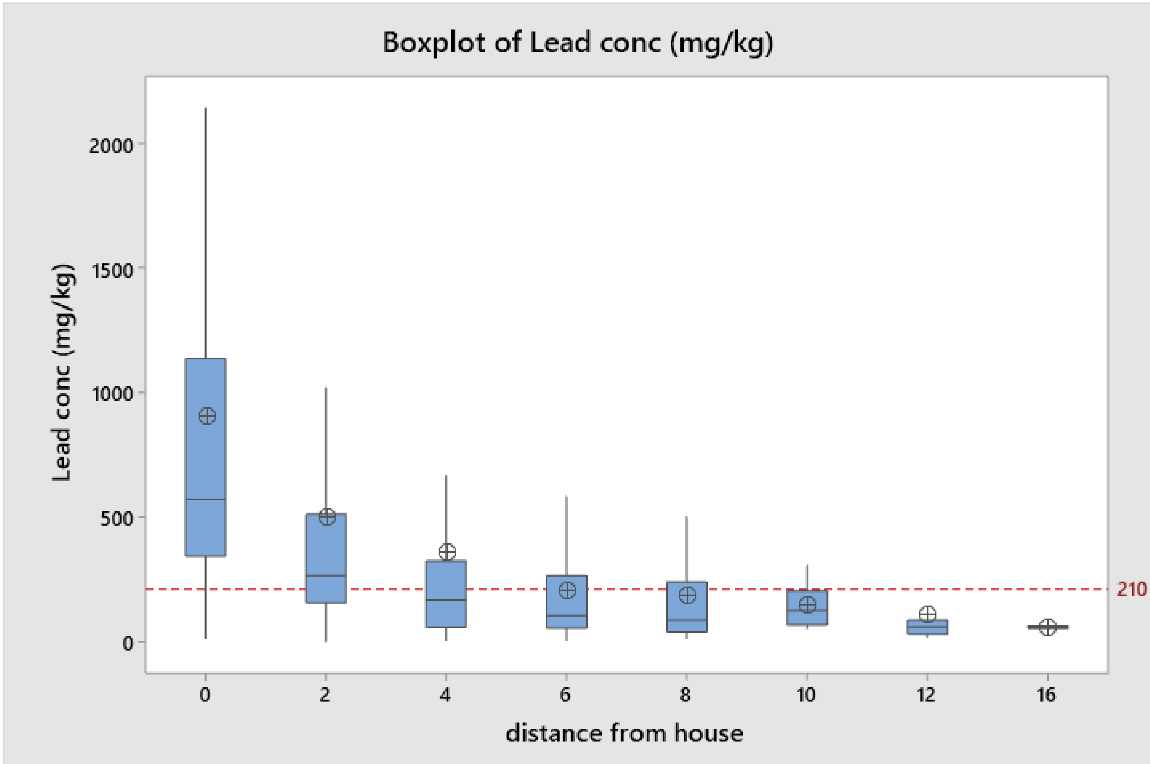

Figure 5.4 Box plot of all samples collected across all properties during case study sampling showing mean and distribution of soil lead concentrations at different distances from the painted surfaces with mean value denoted by a plus. Dotted line represents the 210 mg kg^{-1} SGV for lead.

The influence of roads was also considered and distance from sample location to the nearest road was recorded during sampling. In all three properties, the nearest road was the adjacent road with driveway or access to the property. Two properties sampled were located on roads classified as low volume or access by the NZTA ONRC system and the other property was on a primary collector road (New Zealand Transport Agency, 2019). There was a significant difference ($P<0.005$) between the soil lead concentration for the sites as a function of the road classifications. Property AG, adjacent to the primary collector road, exhibited higher soil lead concentrations than properties E and Y, located on low volume or access graded roads. This may be related more to the increased age of property AG relative to the others and will be addressed in more detail in the discussion. There was no significant difference in soil lead concentration at different distances from the road although there was an apparent trend of lead increasing away from the road up to 24m then decreasing (Figure 5.5). The pattern shown in Figure 5.5 may be influenced predominantly by lead-based paint rather than fuel additives, with the front of the house 14m back from the road for each property. The lower concentrations along the sides and rear of the property compared to the road facing side are not consistent with patterns of lead contamination from a fuel emissions source.

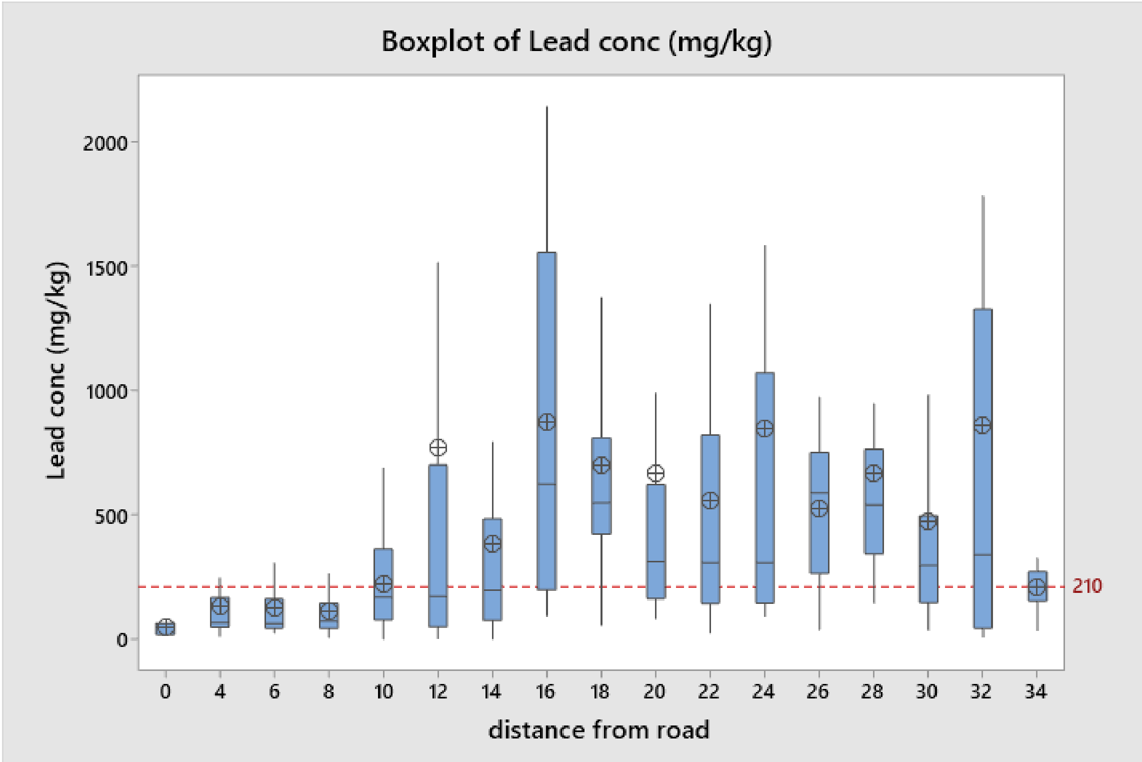

Figure 5.5 Box plot of all samples collected across all properties during case study sampling showing mean and distribution of soil lead concentrations at different distances from the adjacent road with mean value denoted by an x. Dotted line represents the 210 mg kg^{-1} SGV for lead.

5.3 Case Study One (AG)

5.3.1 Soil Lead Concentration

Case study one (AG) was a weatherboard clad home first constructed in the 1900's within Palmerston North City. This section presents the spatial and vertical distribution of lead across property AG using all samples collected (n=126). Samples were collected from locations defined by a 2m grid across the property taking samples at all accessible locations across the property. Soil lead concentrations ranged from below predicted background levels to 7535mg kg^{-1}. The mean soil lead concentration was 841mg kg^{-1} and a median concentration of 412mg kg^{-1} (Figure 5.1). The mean, median and 77% (n=47) of individual samples collected exceeded the 210mg kg^{-1} SGV for residential soils (Ministry for the Environment, 2011a). The vertical and spatial distribution of lead in soils across the property is detailed here.

5.3.2 Vertical Distribution of Lead

For property AG, the mean soil lead concentration was significantly different ($P<0.005$) between sample depths with samples collected at 0-10cm depth having higher soil lead concentrations than samples from 10-20cm depth (Figure 5.6). Both depths had samples with soil lead concentrations at or below background concentrations (Landcare Research, 2015). Both depth layers had soil lead concentrations well exceeding the 210mg kg^{-1} SGV with maximum concentrations of 7535mg kg^{-1} (0-10cm) and 5264.8 mg kg^{-1} (10-20cm). The mean and median soil lead concentrations of both sample depths exceeded the 210mg kg^{-1} lead SGV (Figure 5.6) (Ministry for the Environment, 2011a). The lead concentrations exceeding 1000mg kg^{-1} in samples collected from the lower 10-20cm depth horizon were predominantly taken from garden areas with disturbed, well mixed soils. They were also within 0-2m of the nearest painted surface. Both factors may have resulted in increased soil lead concentrations in the 10-20cm depth. An exception to this is the samples collected from the rear of the property where elevated soil lead concentrations were found without any painted structures suggesting another source of lead (Figure 5.8b).

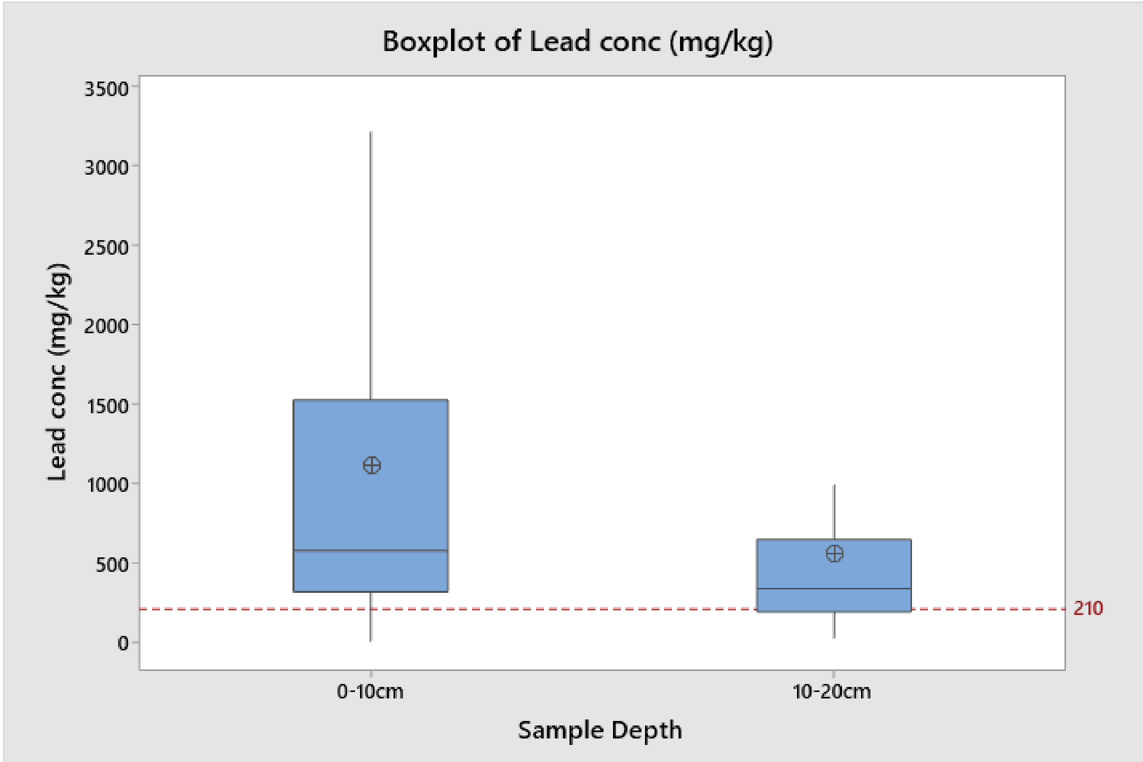

Figure 5.6 Property AG soil lead concentrations in mg kg^{-1} by depth of sample with the mean value denoted by an x. Dotted line represents the 210 mg kg^{-1} SGV for lead.

5.3.3 Lateral Distribution of Lead

For all property AG samples combined, there was a significant difference in soil lead concentrations between samples collected adjacent to the house and all other distances ($P<0.005$). The mean soil lead concentrations adjacent to the house were 1537mg kg^{-1} and decreased away from the house with the lowest mean of 18mg kg^{-1} found 12m away from the nearest painted structure (Figure 5.7). There was no significant difference in soil lead concentrations between samples 2m or further away from a painted structure (Figure 5.7). However, there was a trend of decreasing mean soil lead concentrations with distance from the house with a 45% decrease between 0m and 2m from the house. Further reductions of mean soil lead concentrations by 26%, 41% and 19% were found at

4m, 6m and 8m distance from the house respectively (Figure 5.7). This trend of decreasing concentration was seen at both sample depths. A stronger statistical relationship was found between distance from house and soil lead concentration in samples collected from 0-10cm depth than for the 10-20cm layer. Samples collected from the 0-10cm depth adjacent to the painted structure or house showed significantly higher ($P<0.0005$) lead concentrations than any other distance (Figure 5.7a). Conversely, samples collected from 10-20cm depth showed no significant difference ($P>0.05$) in soil lead concentration with distance from the house (Figure 5.7b). The samples collected 8m ($n=4$) and 12m ($n=2$) away from a painted structure did not have a sufficient population size to allow for significance testing so were removed from the analysis. The mean and median values for distances 0m, 2m, 4m and 6m from the nearest painted structure all exceeded the soil lead SGV of 210 mg kg^{-1} (Figure 5.7) (Ministry for the Environment, 2011a). The results were similar for the 10-20cm layer with the exception of samples collected 6m away having both mean and median values less than the SGV (Figure 5.7b).

(a)

(b)

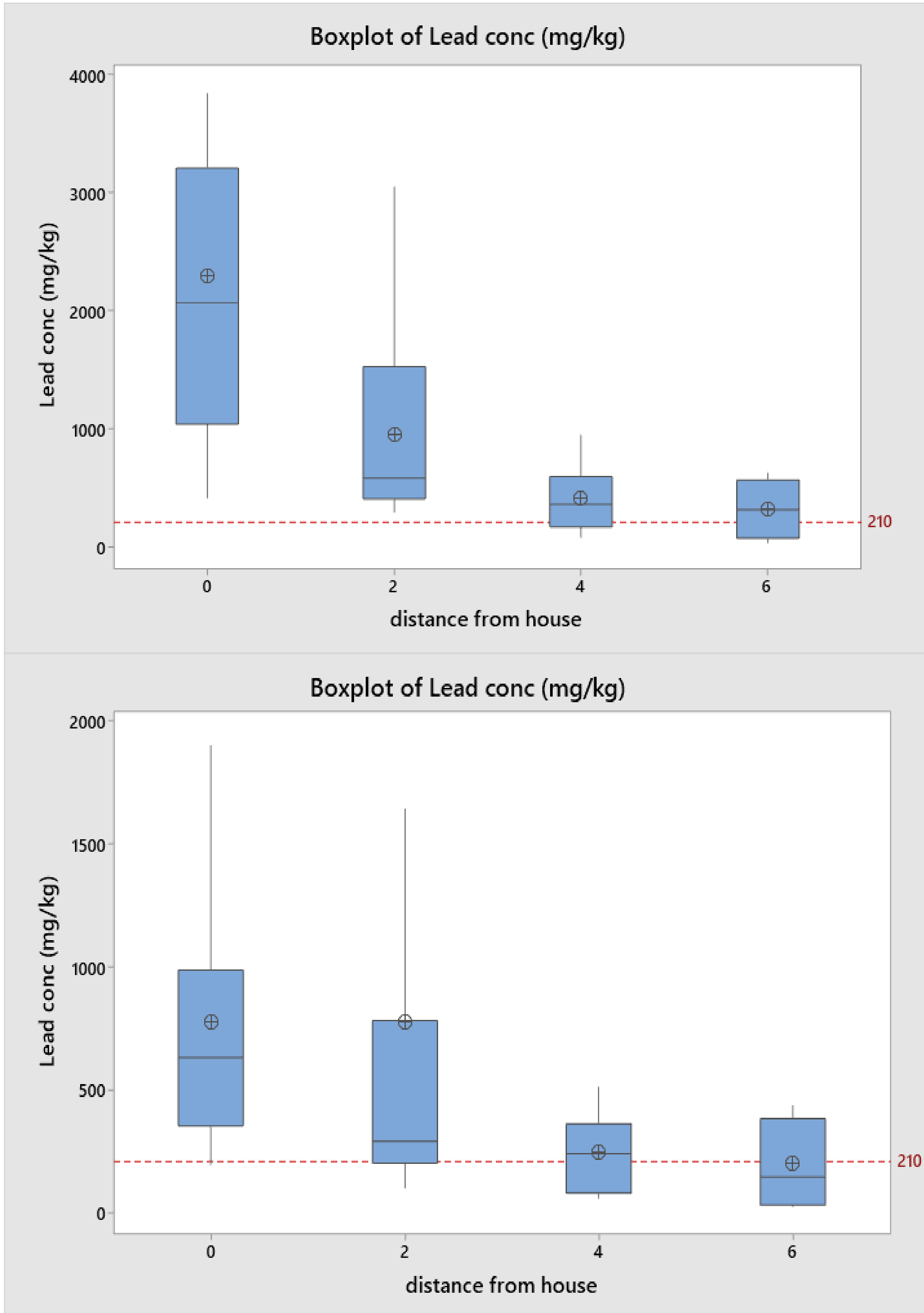

Figure 5.7 Property AG soil lead concentrations in mg kg^{-1} by distance to house (m) for 0-10cm (a) and 10-20cm (b) sample depths. Mean values are denoted by a plus. The dotted line represents the 210 mg kg^{-1} SGV for lead.

The soil lead concentrations for property AG has been presented as an interpolated surface using inverse distance weighted function on ArcMAP for depth 0-10cm (Figure 5.8a) and 10-20cm (Figure 5.8b). The interpolated surface shows a clear pattern around the house with soil lead concentrations decreasing further away from the house. This is more defined at 0-10cm depth compared to 10-20cm depth which is consistent with the properties E and Y. There are several hotspots of lead on the property, one around the garage and another towards the rear of the property. The samples at the rear of the property had soil lead concentrations at both sample depths in excess of 1000mg kg^{-1}.

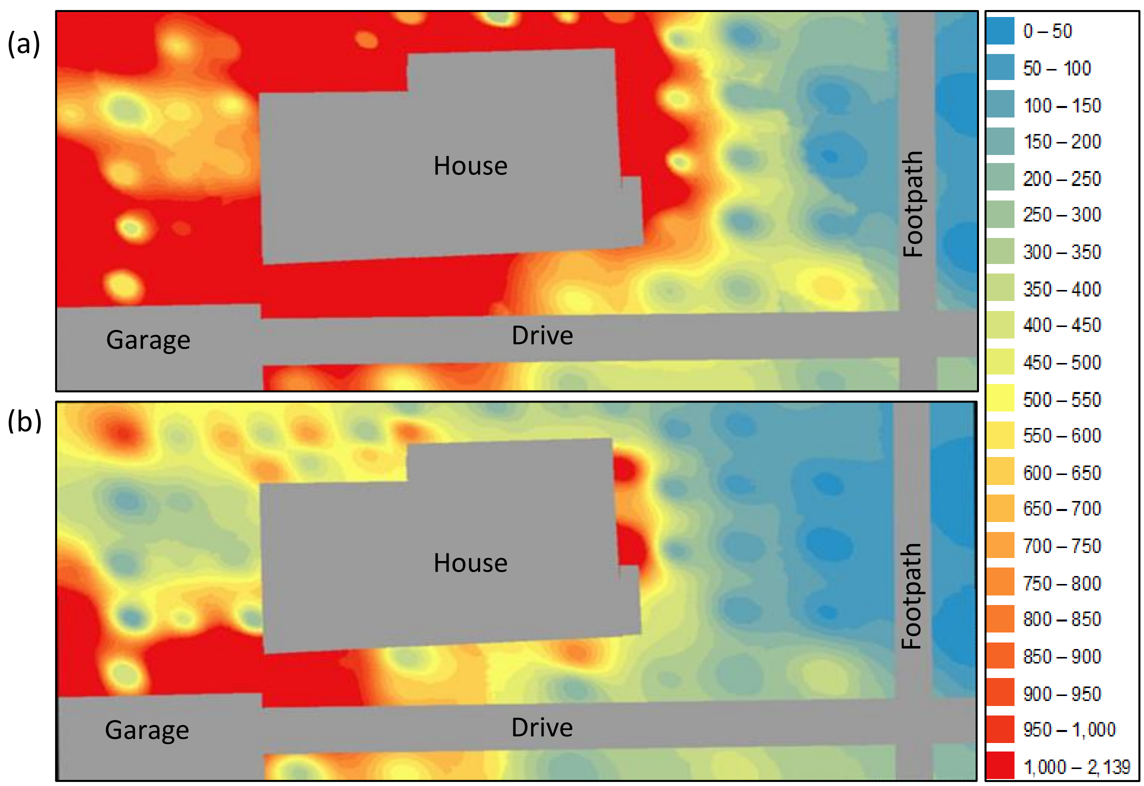

Figure 5.8 Inverse distance weighted interpolation of soil lead concentrations for 0-10cm depth (a) and 10-20cm depth (b) for property AG with scale representing lead concentrations in mg kg^{-1}. Grey areas represent impermeable surfaces and areas unable to be sampled. Road frontage is to the right of the figure.

There was no significant difference between soil lead concentrations as a function of distance to the road (Figure 5.9). Soil samples for property AG were also grouped based on distance from the road and position of the house into three categories; front yard (0m-10m), house curtilage (12m-24m) and back yard (26m-32m).The mean soil lead concentrations generally increased with distance from the road and then decreased into the back yard with the exception of 12m and 32m from the road. The front yard samples had a mean soil lead concentration of 217mg kg^{-1}, which was 82% less than for samples collected from around the house (1230mg kg^{-1}) and 76% lower than samples collected from the backyard (926mg kg^{-1}). The mean soil lead concentration of backyard samples was 24% lower than for samples collected around the house. The higher mean soil lead concentrations in the backyard at 32m from the road were collected along the boundary fence of the property and skewed by two very high samples in excess of 2000mg kg^{-1}.

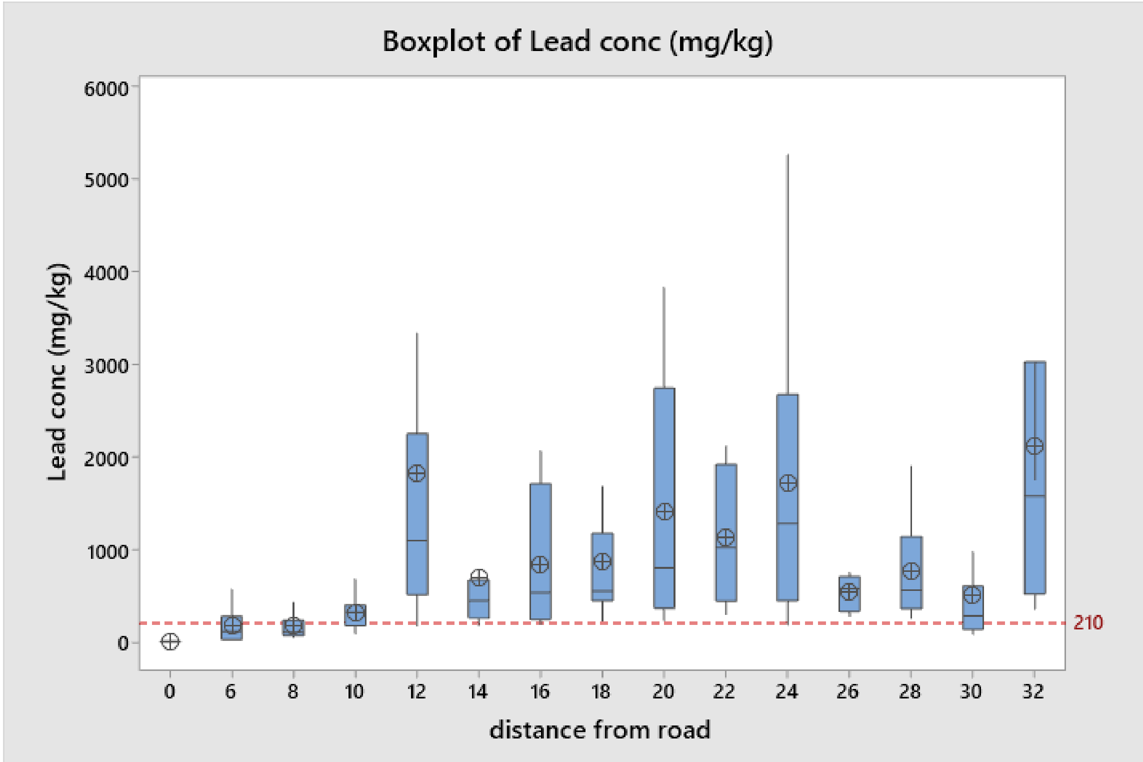

Figure 5.9 Property AG soil lead concentrations in mg kg^{-1} by distance to adjacent road in meters with the mean value denoted by a plus. Dotted line represents the 210 mg kg^{-1} SGV for lead.

5.4 Case Study Property Two (Y)

5.4.1 Soil Lead Concentrations

Case study two (Y) was a weatherboard clad home first constructed in the 1930's within Palmerston North City. This property was undergoing a renovation but the paint had not been stripped back at the time of sampling. This section presents the lateral and vertical distribution of lead across the property using all samples collected (n=128). Samples were collected from locations defined by a 2m grid across the property taking samples at all accessible locations. Soil lead concentrations ranged from 2mg kg^{-1} to 2140mg kg^{-1} (Figure 5.1). The mean soil lead concentrations for property Y were 308mg kg^{-1} and 123mg kg^{-1} respectively, for all samples combined (Figure 5.1). The mean soil lead concentration and

37% (n=47) of samples collected exceeded the 210mg kg^{-1} SGV for residential soils while the median value was less than the SGV (Ministry for the Environment, 2011a). The vertical and lateral distribution of lead in soils across the property is presented in more detail here.

5.4.2 Vertical Distribution of Lead

On property Y, the mean soil lead concentrations between the two sampling depths was found to be significantly different ($P<0.0005$), with samples collected at 0-10cm depth having elevated soil lead concentrations compared to the 10-20cm depth. Both depths had samples with concentrations at or below predicted background concentrations (Landcare Research, 2015). Both depth layers had soil lead concentrations well exceeding the 210mg kg^{-1} SGV with maximum concentrations of 2140mg kg^{-1} (0-10cm) and 1833mg kg^{-1} (10-20cm). The mean soil lead concentration for both sample depths exceeded the 210mg kg^{-1} lead SGV but both median values were below the SGV (Figure 5.10) (Ministry for the Environment, 2011a). Soil lead concentrations exceeding 1000mg kg^{-1} in samples collected from the 10-20cm depth were all collected from garden areas adjacent to the house with highly disturbed soils.

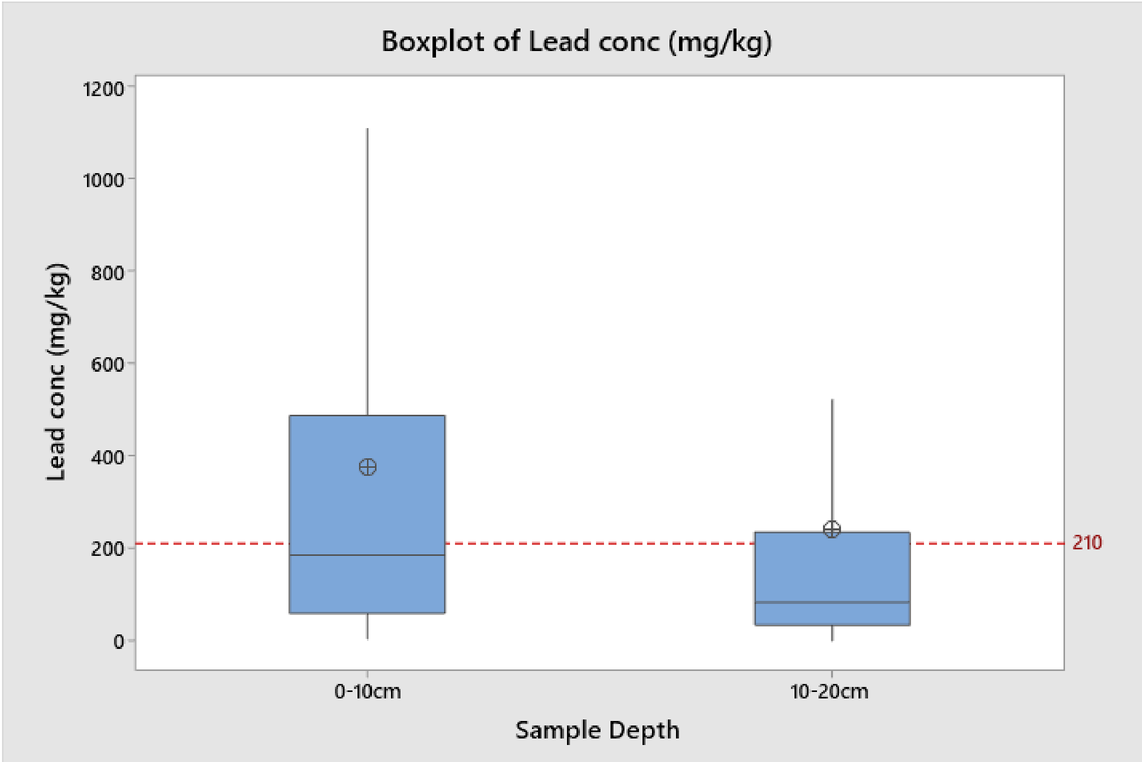

Figure 5.10 Property Y soil lead concentrations in mg kg^{-1} by depth of sample with the mean value denoted by a plus. Dotted line represents the 210 mg kg^{-1} SGV for lead.

5.4.3 Lateral Distribution of Lead

For all property Y samples combined, there was a significant difference in soil lead concentrations between samples collected adjacent to the house and at all other distances (<0.0005). The mean concentration was highest adjacent to the house (715mg kg^{-1}) and generally decreased away from the house with the lowest mean concentration of 41mg kg^{-1} found 8m away from the nearest painted structure (Figure 5.11). There was no significant difference in soil lead concentrations found between samples 2m or further away from a painted structure (Figure 5.11). The mean soil lead concentration at property Y decreased more rapidly with distance from the house than at property AG, with an 82% decrease between 0m and 2m from the house. Further reductions of mean soil lead concentrations by 12%, 42% and 39% were found at 4m, 6m and 8m distance from the house respectively (Figure 5.11). This trend of decreasing soil lead concentration was seen at both sample depths. There was a statistically significant relationship found between distance from house and soil lead concentration in samples collected from 0-10cm depth. Samples collected adjacent to the house at 0-10cm depth showed significantly higher ($P<0.0005$) lead concentrations than any other distance (Figure 5.11a). Conversely, samples collected from 10-20cm depth showed no significant difference ($P>0.05$) in soil lead concentrations with distance from the house (Figure 5.11b). The mean and median values for samples taken adjacent (0m) to the house at 0-10cm depth exceeded the lead SGV of 210 mg kg^{-1} (Ministry for the Environment, 2011a). The soil lead concentration (mean and median) for all other sample distances at 0-10cm depth and all samples distances at 10-20cm depth had values less than the SGV (Figure 5.11).

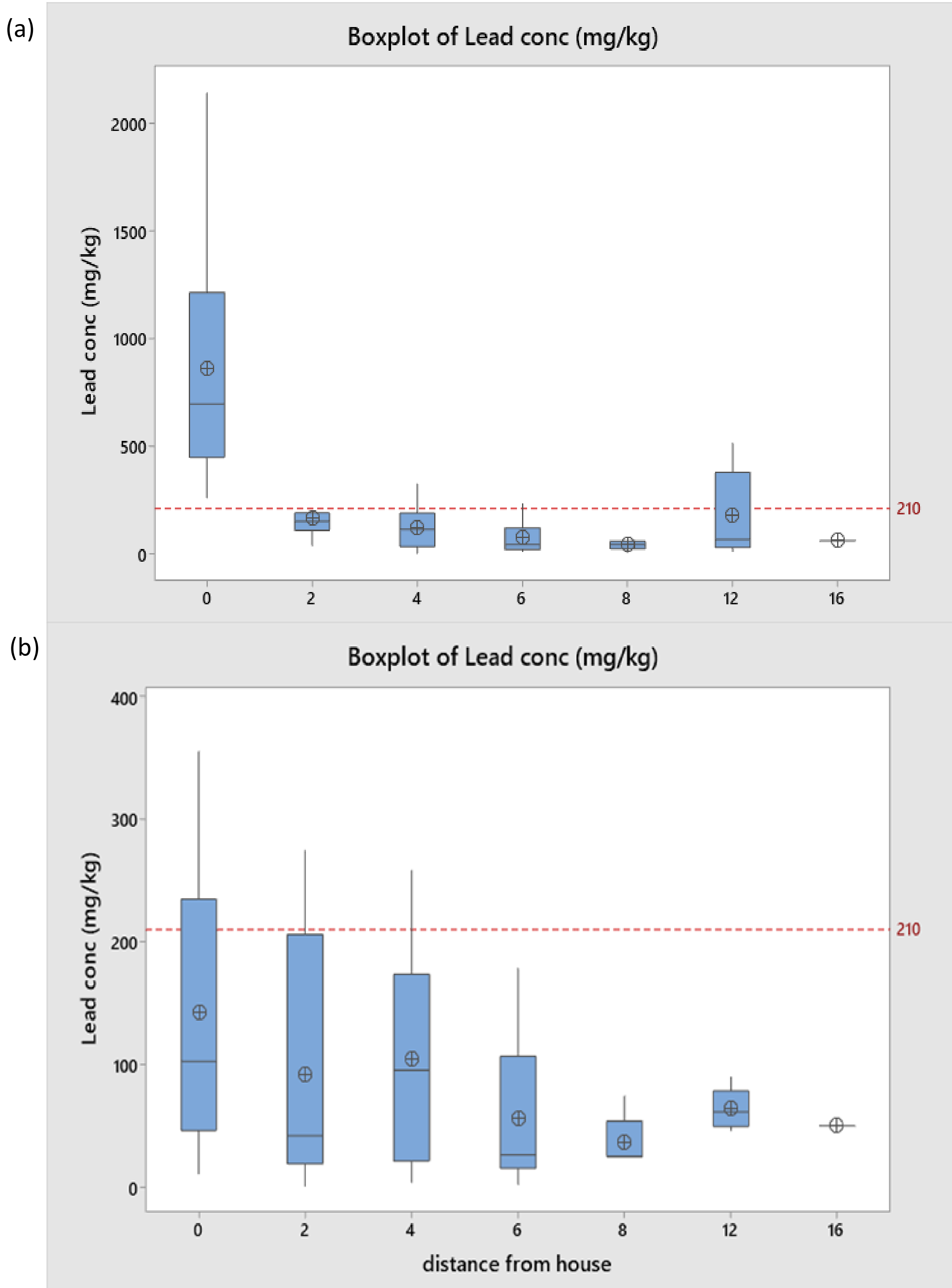

Figure 5.11 Property Y soil lead concentrations in mg kg^{-1} by distance to house (m) for 0-10cm (a) and 10-20cm (b) sample depths. Mena values are denoted by a plus. The dotted line represents the 210 mg kg^{-1} SGV for lead.

The soil lead concentrations for property Y have been presented for samples collected from 0-10cm depth (Figure 5.12a) and 10-20cm depth (Figure 5.12b) as an interpolated surface using distance weighted interpolation. The interpolated surface shows a clear pattern of soils lead distribution around the property with concentrations greatest closest to the house and decreasing with distance away from the house. This pattern is more prominent in the 0-10cm layer than the 10-20cm layer which is consistent with property AG. Hotspots present at both upper and lower levels were all samples collected from well cultivated garden soils. The elevated concentration within the lower layer towards the rear of the house that is not detected in the upper layer was in an area of building material and is believed to represent well mixed flakes of paint. Samples collected from around the curtilage of the house had soil lead concentrations in excess of 1000mg kg^{-1}. For property Y, no samples further than 2m from the house exceeded a concentration of 1000mg kg^{-1}.

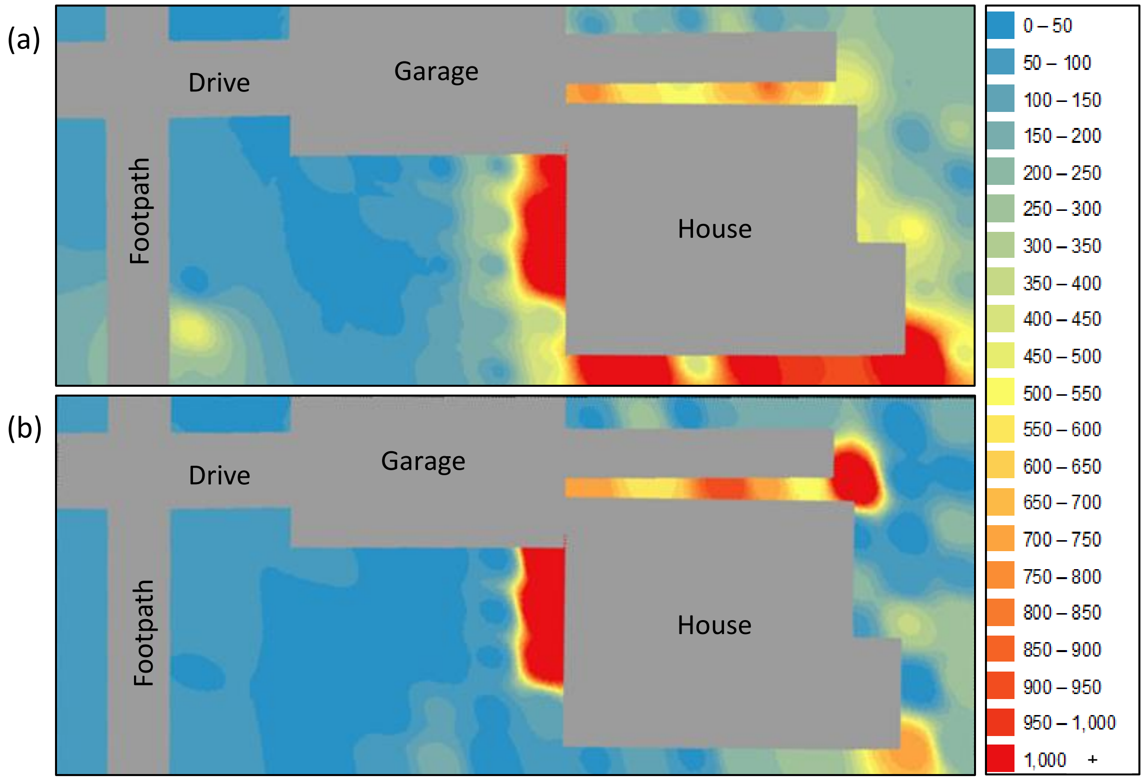

Figure 5.12 Inverse distance weighted interpolation of soil lead concentrations for 0-10cm depth (a) and 10-20cm depth (b) for property Y with scale representing soil lead concentrations in mg kg^{-1}. Grey areas represent impermeable surfaces and areas unable to be sampled. Road frontage is to the left of the figure.

For property Y, there was no significant difference between soil lead concentrations as a function of different distances to the road (Figure 5.13). The soil lead concentrations are at or below background concentrations until adjacent to the front of the house which had a mean soil lead concentration of 1000mg kg^{-1}. This pattern of lead contamination being highest along the road frontage may be indicative of a leaded petrol source for some of the soil lead found. The soil lead concentrations then decrease towards the rear of the property (Figure 5.13). Soil samples for property Y were also grouped based on distance from road and position of the house into three categories; front yard (0m-14m), house curtilage (16m-28m) and back yard (30m-34m). The mean soil lead concentration for the front yard (67mg kg^{-1}) was 89% less than that for samples collected from around the house (627mg kg^{-1}) and 78% lower than samples collected from the backyard (302mg kg^{-1}). The mean soil lead concentration of backyard samples was 52% lower than for samples collected around the house (507mg kg^{-1}).

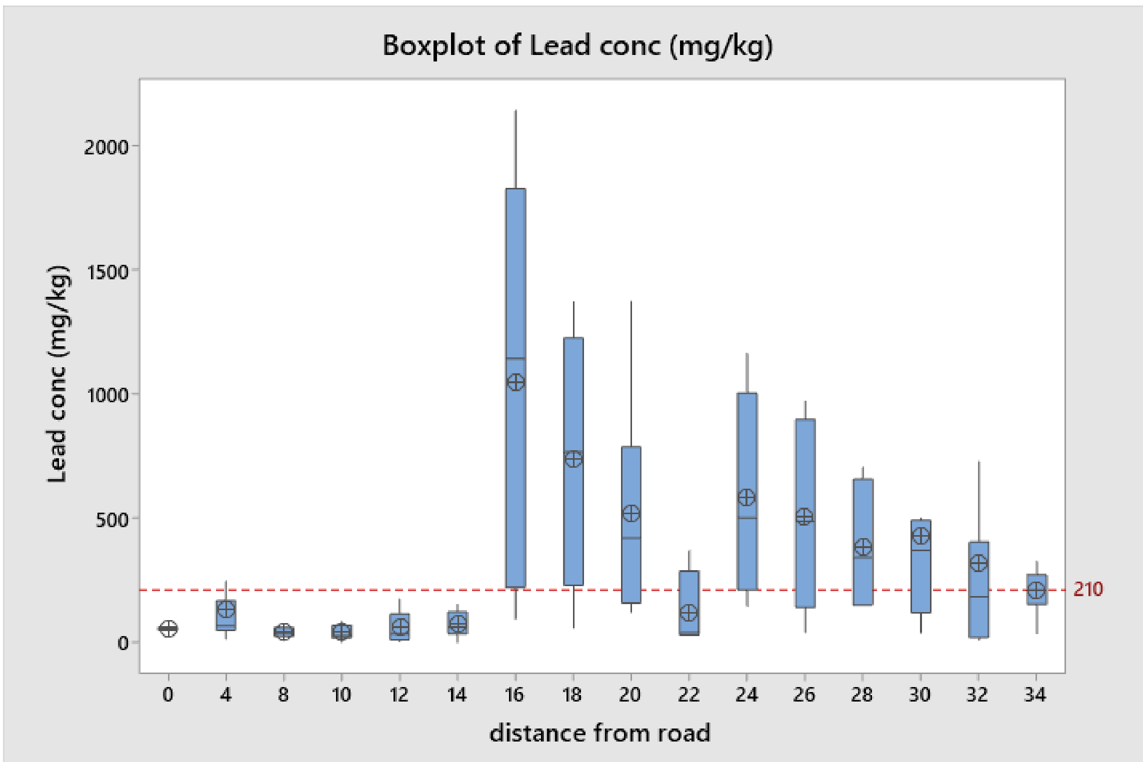

Figure 5.13 Property Y soil lead concentrations in mg kg^{-1} by distance to adjacent road in meters with the mean value denoted by a plus. Dotted line represents the 210 mg kg^{-1} SGV for lead.

5.5 Case Study Property Three (E)

5.5.1 Soil Lead Concentrations

Case study three (Property E) was a weatherboard clad home constructed in the 1930's within Palmerston North City, similar to property Y. The parcel size was less than that of property Y and it had been renovated by the owner approximately 20 years ago. This section presents the lateral and vertical distribution of lead across Property E using all samples collected (n=85). Samples were collected from locations defined by a 2m grid across the property taking samples at all accessible locations. Soil lead concentrations ranged from 33mg kg^{-1} to 1019mg kg^{-1} (Figure 5.1). The mean lead concentration was 246mg kg^{-1} and the median concentration was 168mg kg^{-1} (Figure 5.1). The mean soil lead concentration and 40% (n=34) of samples collected exceeded the 210mg kg^{-1} SGV for residential soils while the median value was less than the SGV (Ministry for the Environment, 2011a). The vertical and lateral distribution of lead in soils across the property is presented in more detail here.

5.5.2 Vertical Distribution of Lead

On property E, the mean soil lead concentration was not found to be significantly different (P=0.449) between sample depths with the 0-10cm horizon having only a nominally higher lead concentration compared to the 10-20cm depth (Figure 5.14). Both depths had samples with soil lead concentrations at or below background concentrations (Landcare Research, 2015). Both depth layers had soil lead concentrations well exceeding the 210mg kg^{-1} SGV with maximum concentrations of 1019mg kg^{-1} (0-10cm) and 986mg kg^{-1} (10-20cm). The mean soil lead concentrations of both sample depths exceeded the 210mg kg^{-1} lead SGV but median values for both depths were below the SGV (Figure 5.14) (Ministry for the Environment, 2011a). Notably, no soil samples collected from the lower 10-20cm depth on property E had soil lead concentrations exceeding 1000mg kg^{-1}. The reported concentrations found at property E were significantly lower than those reported for property AG (P<0.005) but not significantly different to those found on property Y (Figure 5.1).

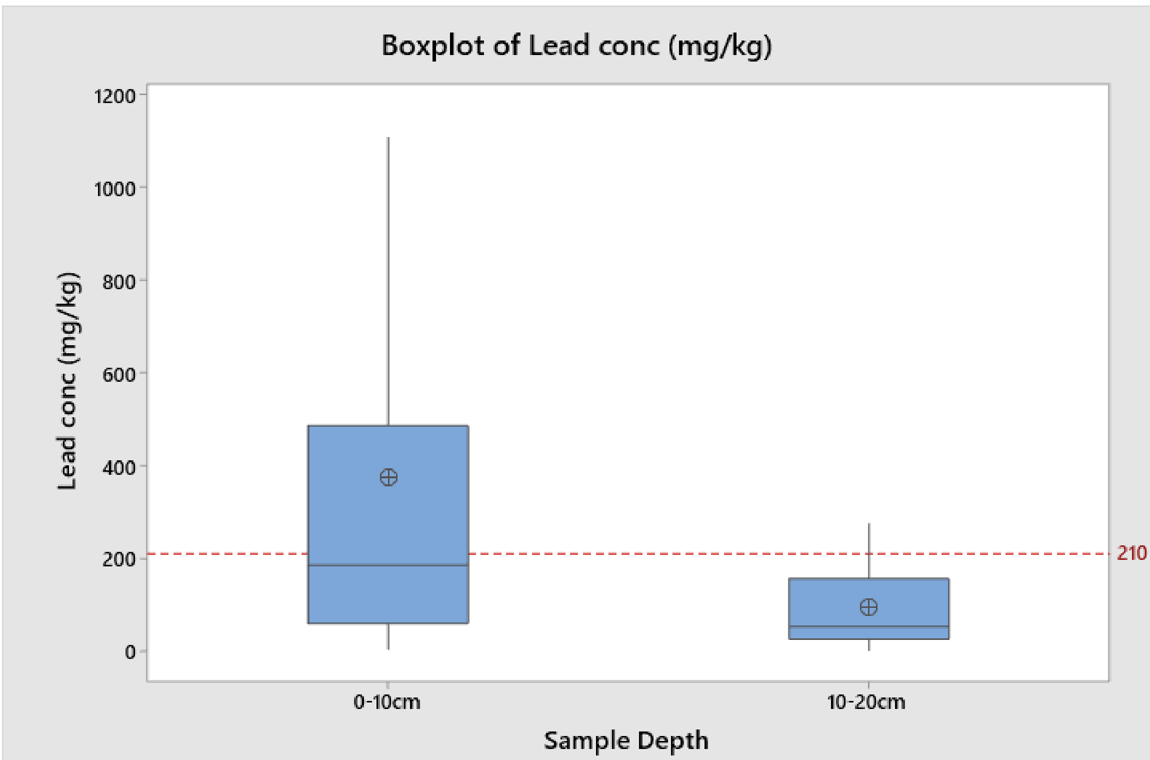

Figure 5.14 Property E soil lead concentrations in mg kg^{-1} by depth of sample with the mean value denoted by a plus. Dotted line represents the 210 mg kg^{-1} SGV for lead.

5.5.3 Lateral Distribution of Lead

For all property E samples, there was a significant difference in soil lead concentrations between samples collected adjacent to the house and at all other distances (P<0.0005).

The mean soil lead concentrations were highest in samples taken adjacent to the house (441mg kg^{-1}) and generally decreased away from the house, with the lowest mean concentration (58mg kg^{-1}) found 4m away from the nearest painted structure (Figure 5.15). There was no significant difference in soil lead concentrations found between samples 2m or further away from a painted structure (Figure 5.15). The mean soil lead concentrations for property E decreased with distance from the house with a 47% reduction over the 2m between 0m and 2m. There was a further reduction in soil lead concentrations by 75% between 2m and 4m from the house. The mean soil lead concentrations then increased from 4m with a hotspot in the backyard influencing the distribution pattern (Figure 5.16). This hotspot was not located near any painted structure and had no obvious lead paint source nearby. This trend with distance was seen at both sample depths; there was a statistically significant relationship found between distance from house and soil lead concentration in samples collected from both the 0-10cm and 10-20cm depths ($P<0.0005$) (Figure 5.15). Samples collected adjacent to the painted structure or house showed significantly higher lead concentrations than any other distance at both sample depths (Figure 5.15). The mean and median values for samples taken adjacent to (0m) and 2m from painted structures at 0-10cm, and for adjacent samples (0m) at 10-20cm depth exceeded the lead SGV of 210mg kg^{-1} (Ministry for the Environment, 2011a). All other samples collected at 0-10cm and 10-20cm had mean and median values less than the SGV (Figure 5.15b).

(a)

(b)

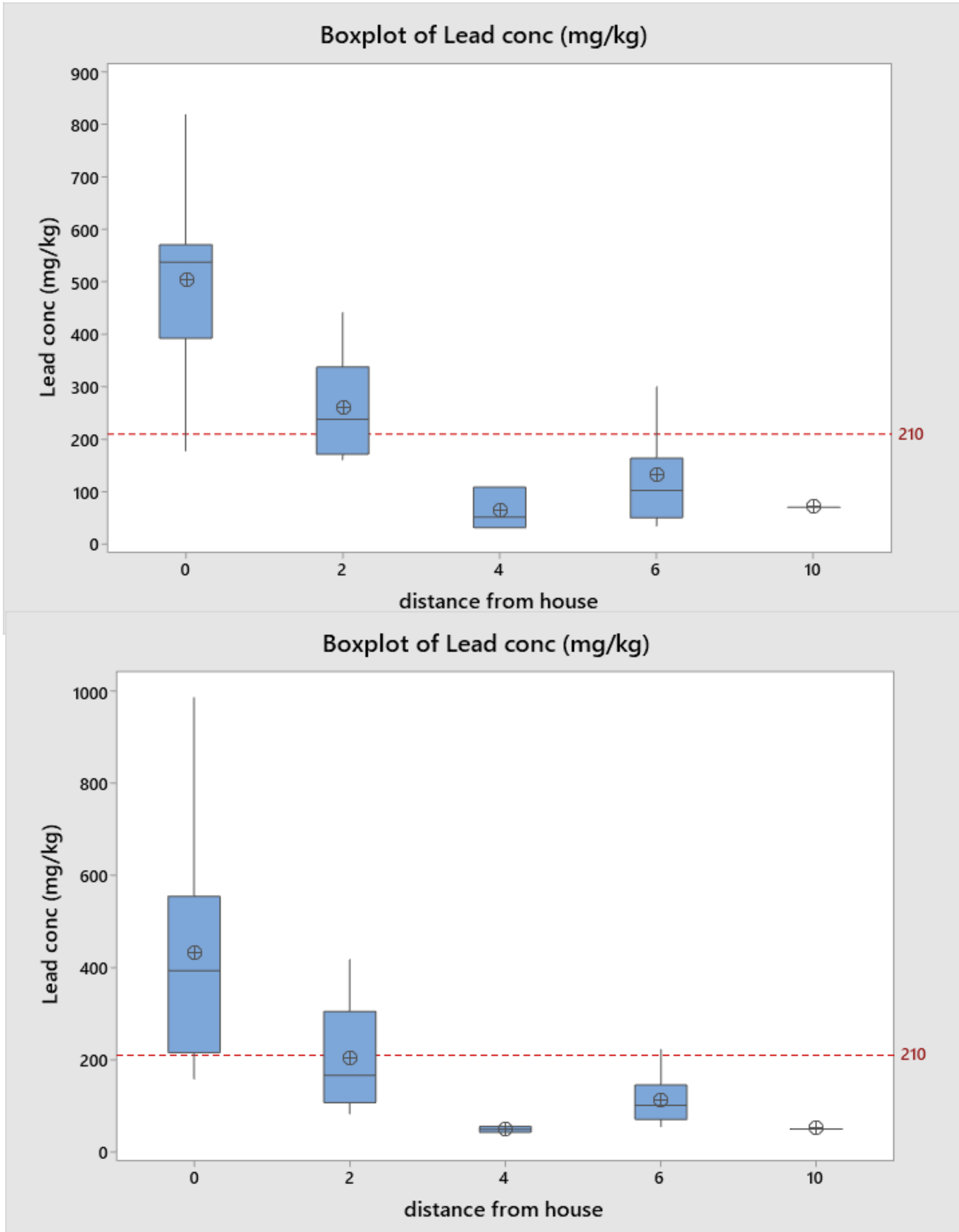

Figure 5.15 Property E soil lead concentrations in mg kg^{-1} by distance to house (m) for 0-10cm (a) and 10-20cm (b) sample depths. Mena values are denoted by a plus. The dotted line represents the 210 mg kg^{-1} SGV for lead.

The soil lead concentrations for property E have been presented for the 0-10cm depth (Figure 5.16a) and 10-20cm depth (Figure 5.16b) as an interpolated surface using inverse distance weighted interpolation. The interpolated surface shows a clear pattern around the property with soil lead concentrations decreasing with distance away from the house, similar to property AG and Y. The pattern is not as distinct as in properties AG and Y and there is little variation between the upper and lower sample depths. This is consistent with the analysis not showing a significant difference between the two sample depths on property E. There are several hotspots of elevated lead concentrations on the property. One is near the driveway in a well-mixed garden bed and shows higher concentrations in the 10-20cm sample depth compared to the 0-10cm depth (Figure 5.16). Another hotspot is in the rear garden of the property with a soil lead concentration exceeding 1000mg kg^{-1} within the 0-10cm layer (Figure 5.16a). A review of historical information and observations onsite were unable to confirm the cause of this elevated level. It is possible that surface soil from around the curtilage of the property could have been redistributed in this location, or this may have been an area for preparation of lead-based paint in the past.

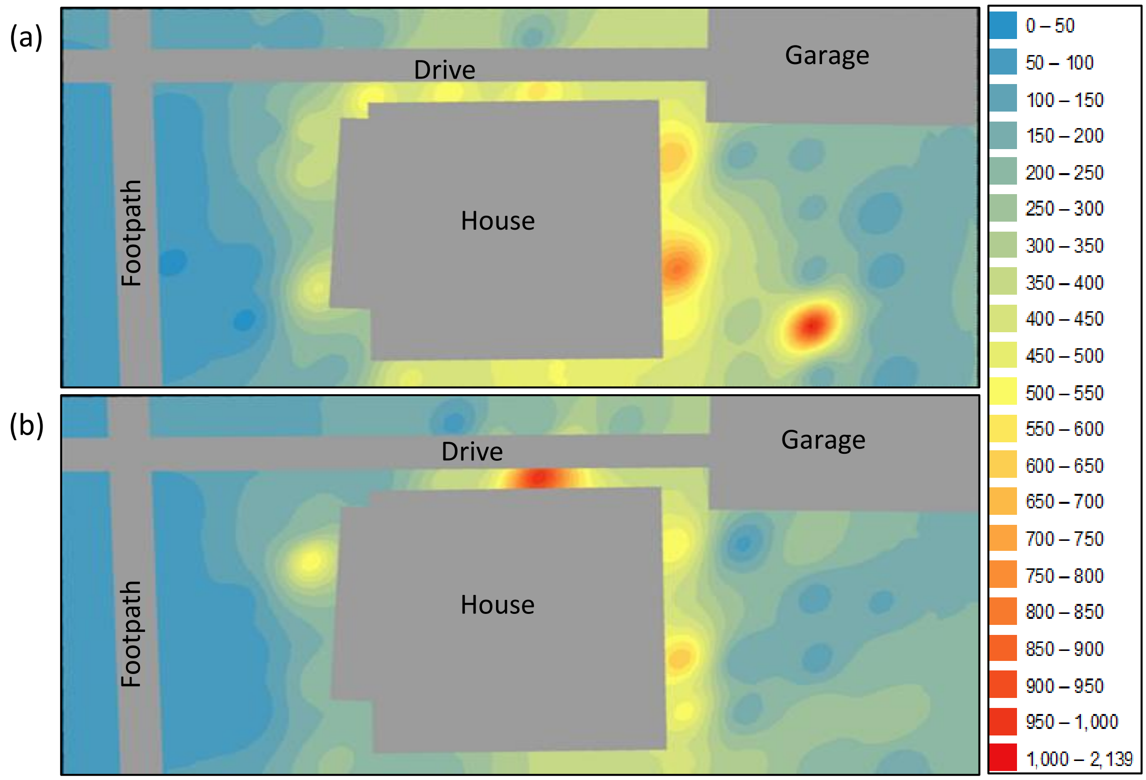

Figure 5.16 Inverse distance weighted interpolation of soil lead concentrations for 0-10cm depth (a) and 10-20cm depth (b) for property E with scale representing lead concentrations in mg kg^{-1}. Grey areas represent impermeable surfaces and areas unable to be sampled. Road frontage is to the left of the figure.

For property E, there was no significant difference found between soil lead concentrations of samples as a function of distance to the road (Figure 5.17). Soil samples for property E were grouped based on distance from road and position of the house into three categories; front yard (0m-8m), house curtilage (10m-18m) and back yard (20m-24m). The mean soil lead concentrations were lowest in the front yard, increased away from the road and then decreased across the property backyard (Figure 5.17). Mean soil lead concentrations in the front yard (75mg kg^{-1}) were 80% less than for samples collected around the house (382mg kg^{-1}) and 67% lower than the mean soil lead concentration for backyard samples (224mg kg^{-1}). The mean for backyard samples was 41% lower than that for samples collected around the house. The pattern of soil lead concentrations does not indicate that lead additives in fuels have been a significant contributor to soil lead concentrations on property E.

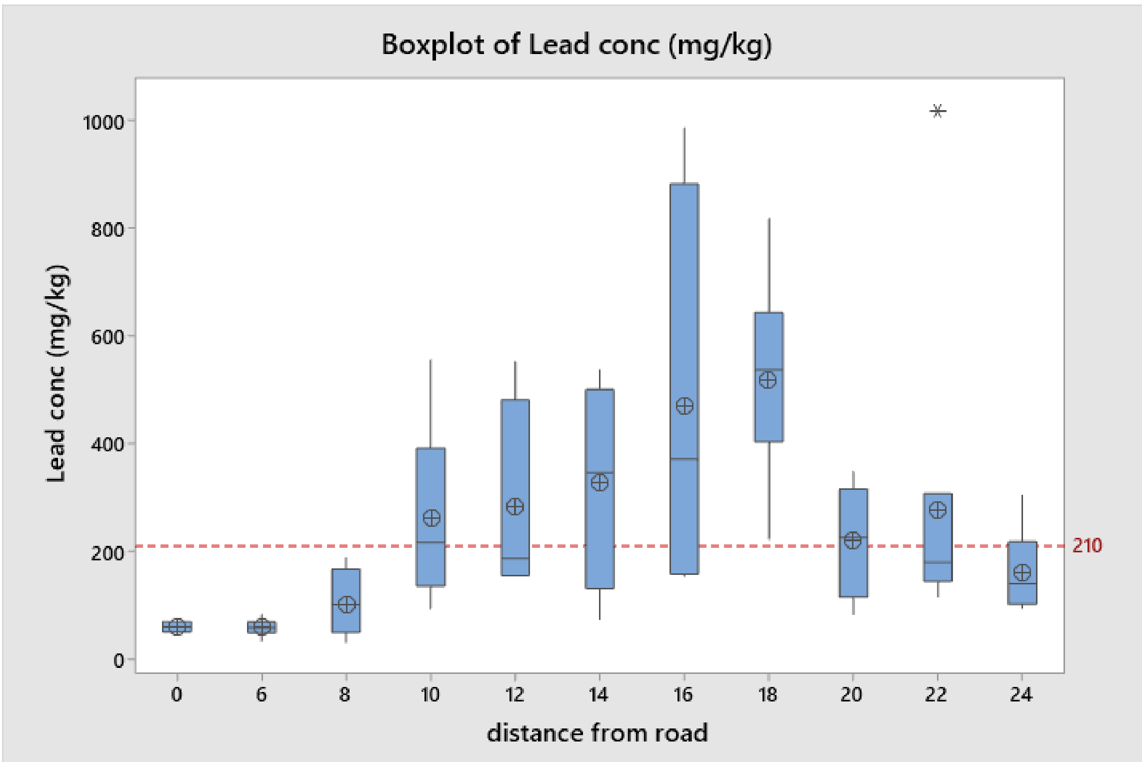

Figure 5.17 Property E soil lead concentrations in mg kg^{-1} by distance to adjacent road in meters with the mean value denoted by an x. Dotted line represents the 210 mg kg^{-1} SGV for lead.

5.6 Discussion

The results of the case study investigation into three systematically sampled residential properties in Palmerston North City has demonstrated lateral and vertical variations in soil lead concentrations on properties consistent with lead-based paint contamination. The delineation of soil lead across residential properties that could be considered average for Palmerston North allows for better informed management and remediation decisions for affected properties. Previous studies have focussed on collecting a large volume of data across multiple properties as the current study addressed in Chapter Four (Jacobs et al, 2002; Jordan & Hogan, 1975; Kandic et al, 2019; Rouillon et al, 2017; Seyefardalan et al, 2017). Previous studies have also targeted sampling locations in areas where exposure is most likely to occur such as vegetable gardens (Clark et al, 2015; Laidlaw et al, 2018), garden soils (Seyefardalan et al, 2017), from key locations such as the dripline and entrance of a house (Jacobs et al, 2002; United States Environmental Protection Agency, 1995), or from user submitted samples taken at various locations (Kandic et al, 2019; Rouillon et al, 2017). Between one and ten samples were collected from different areas of properties investigated in previous studies (Table 2.1), and this sampling approach may overestimate or underestimate soil lead concentrations depending on sample depth and location. The higher sample density of the current study allowed for more accurate interpolation of soil lead concentrations to create a spatial representation of soil lead concentrations at the investigated properties with greater accuracy than through the use of transects or targeted sampling (Figure 5.8, Figure 5.11 and Figure 5.16). To the knowledge of the author, this study presents the most high-definition investigation into lead-based paint contamination at residential properties in a regional New Zealand city.

5.6.1 Lateral Distribution of Lead

The lateral variation of soil lead at all three case study properties showed a distinct pattern with significantly higher concentrations adjacent to the houses or outbuildings and decreasing soil lead concentrations with distance (Figure 5.8, Figure 5.11 and Figure 5.16). The interpolated surfaces show several hotspot locations on properties AG and Y that were unable be explained by the current presence of painted structures. Investigation into historical aerial photography and satellite imagery of these properties available did not reveal any obvious source for the elevated soil lead concentrations, such as previous outbuildings. On property AG, anecdotal evidence from the owner suggests that there was a stable associated with the house in the general location of the rear hotspot in the early 1900’s which may be the source of elevated lead, potentially from lead head nails that were found in one sample. There was another obvious hotspot on property AG in samples collected from soil that had recently been disturbed with the installation of an air conditioning unit. It is presumed that lead-based paint contaminated soil from near the house was dug out during the installation and placed further away from the property leading to a hotspot. The hotspot shown on property E encompassed recent garden soils and undisturbed lawn soils and could not be explained by the presence of current or historical painted structures. It is possible that this could be associated with an older outbuilding not captured by aerial photography or potentially a disposal area for renovation and building material, similar to that found at property AG. Similar hotspots were found by Clark and Knudsen (2014) on intensively sampled properties. These were attributed to the footprint of an older painted structure (Clark & Knudsen, 2014). All three case study properties showed a significant difference in soil lead concentrations between samples collected adjacent to the house compared to all other distances (Figure 5.4). This lateral trend of decreasing concentration with distance from a house is consistent with previous studies (Clark & Knudsen, 2014; Codling, 2013; Jordan & Hogan, 1975). However, this trend was found to be limited to the upper 0-10cm of soil, indicating that deteriorating or renovated lead-based paint is the dominant source for soil lead on residential properties. This trend has also been shown around other urban structures such as telephone boxes, bridge parapets and goalposts with deteriorating lead-based paint (Turner & Lewis, 2018).

Similar investigations to the current study were undertaken by Clark and Knudsen (2014) in the small city of Appleton in the United States and in Christchurch, New Zealand by Jordan and Hogan (1975). These two studies are the only research to be undertaken investigating lead-based paint contamination on residential properties in smaller urban neighbourhoods comparable to the setting of Palmerston North City. The study undertaken by Jordan and Hogan (1975) investigated two properties in Christchurch, New Zealand using transects on each side of the homes and at 4 equal depths to a maximum 40cm depth. One property was an early 1900's weatherboard property that exhibited high soil lead concentrations consistent with the results of the current study (Jordan & Hogan, 1975). The other property was an early 1900's brick building which did not show any significant elevated soil lead concentrations (Jordan & Hogan, 1975). A study by Codling

(2013) investigated the effects of distance and depth on soil lead concentration at two lead-based paint impacted rural properties. The results of this study indicate that rural lead-based paint contamination may exhibit a similar spatial distribution to that found by the current study.

5.6.2 Vertical Distribution of Lead

The findings presented here show significantly decreased soil lead concentrations in the lower 10-20cm depth compared to surface 0-10cm (Figure 5.2). This finding is similar to that reported by previous studies (Codling, 2013; Jordan & Hogan, 1975). However, considerably fewer investigations into the vertical distribution of lead at residential properties have been made compared to lateral distribution studies. The limited number of published studies into the depth distribution of lead-based paint contamination is likely due to the heightened exposure risk from the exposed surface layer compared to underlying soils (Clarke et al, 2015; Kandic et al, 2019; Ministry of Health, 2012). The vertical extent of soil lead concentrations is important to understand when assessing management and remediation strategies for impacted sites. A recent study by Turnbull et al (2019) investigated trace element distribution in Dunedin, New Zealand. They showed evidence of anthropogenic impacts, including elevated soil lead concentrations, present in urban soils to 70cm depth (Turnbull et al, 2019). It is not known if the lead-based paint contamination found in the current study extends to 70cm depth as samples were unable to be collected from depths greater than 20cm at most locations.

During sampling it was noted that the hand augur used to gather the samples at both depths had occasional ‘drag up’ of lower soil levels during sampling. Although utmost care was taken to ensure that the soil core was removed intact without ‘drag up’ it is likely that this may have occurred on some samples. The effect of ‘drag up’ would have been incorporation of deeper lower-concentration soil with the surface horizon, decreasing the reported lead concentration. However, drag up is not considered to have had a material effect on the results of this investigation.

5.6.3 Influence of Roads on Soil Lead

In larger urban centres around the world, there have been strong relationships found between soil lead concentrations and distance to major roads (Clarke et al, 2015; De Silva et al, 2016; Francek et al, 1994; Laidlaw & Filippelli, 2008; Mielke et al, 1983; Mielke et al, 2008). Kandic et al (2019) found that lead concentrations increased with proximity to major roads in Sydney but found no influence of low volume roads on local soil lead concentrations. The spatial pattern exhibited at the three case study properties showed higher soil lead concentrations along the sides and rear of the homes rather than the road-facing side of the house. If the barrier effect shown on residential properties by other studies (Mielke et al, 2008) were a significant influence we would expect to find higher concentrations along the road facing side. Clark and Knudsen (2014) also found that soil lead concentrations generally increased away from the road, using samples collected from the berm, mid lawn and dripline of properties. The results presented in the current study agreed with those found by Clark and Knudsen (2014) with generally increasing soil lead concentrations away from roads (Figure 5.5, Figure 5.9, Figure 5.13 and Figure 5.17). Notably, the six samples collected from the road berm of the properties all reported lead concentrations below 72mg kg^{-1} and the berm samples collected from the property adjacent to a primary collector classified road were below predicted background lead concentrations (Landcare Research, 2015). The results of the current research do not agree with those found by other studies, with no discernible influence of traffic volume/density on soil lead concentrations (Kandic et al, 2019; Laidlaw and Filippelli, 2008; Mielke et al, 2008; Rouillon et al, 2017), however this may be attributed to the setting of these comparative studies in larger urban areas of Los Angeles (Clarke et al, 2015), Melbourne (Kandic et al, 2019; Laidlaw & Filippelli, 2008) and Sydney (Rouillon et al, 2017). Turnbull et al (2019) found that the elevated soil lead concentrations within urban soils of Dunedin could be attributed to both historical use of lead-based paint and leaded petrol, based on isotopic analyses. The findings of the current study suggest that leaded petrol is a negligible contributor to soil lead concentrations on residential properties in Palmerston North City and lead-based paint is the dominant source within the residential urban environment. However, soil lead concentrations around brick clad properties is more likely to be caused by leaded petrol sources than lead-based paint as was shown in Christchurch (Jordan & Hogan, 1975). Further isotopic analyses of the lead in the soil samples would provide source apportionment data and better detail the impact, if any, of leaded petrol on sample properties investigated in this current study.

5.6.4 Case Study Conclusions

This case study investigation has demonstrated that the distribution pattern for soil lead across typical residential properties follows published examples. The results of the current study are similar to previous studies with soil lead concentrations decreasing with depth and distance from the house (Clarke & Knudsen, 2014; Codling, 2013; Jordan & Hogan, 1975). The highest soil lead concentrations at each case study property were found adjacent to the house (0-2m) and significantly exceeded SGVs. The inclusion of flakes of lead-based paint in samples may be the dominant contributor to the very high soil lead concentrations found in some samples adjacent to the house. However, not all samples that exhibited unexpectedly high soil lead concentrations had visible paint flakes during sample preparation. Soil lead concentrations were highest in surface soils (0-10cm) significantly decreasing with depth. A crucial next step in assessing the risk posed by the findings presented in this case study investigation is to investigate the fractionation and bioavailability of lead in residential soils. Determination of grain size distribution, effect of paint flakes and proportion of total lead that is sorbed to soil grains versus lead within paint flakes would add valuable lines of evidence for risk assessment although such work is beyond the scope of the current study. The implications of the findings presented in this chapter are discussed alongside those from the initial investigation in the next Chapter Six. Recommendations for further work and options for managing lead paint impacted residential sites will be presented in this next and final chapter.

6.0 Implications of lead-based paint in soil and recommendations for managing public health

6.1 Implications

The investigations presented in the current study define lateral and vertical trends in soil lead concentration across the soil at residential properties. The results showed that soil lead concentrations decreased with distance from the house, decreased with depth, and increased with age of the house. Weatherboard homes were shown to have significantly higher soil lead concentrations than all other construction types of a similar age group. Importantly, there was no clear trend between soil lead concentrations and distance from road or traffic volume that has been seen in larger urban settings (Clarke et al, 2015; Mielke et al, 2008). The current study only addressed the distribution of lead and did not attempt to quantify the exposure risk to occupants of impacted properties. However, the potential risks defined by the results of this study, as well as possible solutions, are discussed in this chapter, along with recommendations for further work.

6.1.1 Human Health Implications

While exposure risk from elevated soil lead concentrations in sample properties was not directly investigated in this work, housing stock estimates and the results of the current study can be used to estimate the scale of lead-based paint contamination in New Zealand residential soils. Page and Fung (2008) summarised available datasets on housing stock in New Zealand and characterised these into construction periods. When applied to Palmerston North City housing data we can show that there are approximately 15,000 standalone residential properties constructed prior to 1980 which may have elevated soil lead concentrations (Page & Fung, 2008; Statistics New Zealand, 2013). An estimated 80% (12,000) are of weatherboard construction, and are therefore likely to exhibit the greatest level of impacts (New Zealand Yearbook, 1960). There is an estimated 3300 residential properties built before 1940 within Palmerston North City. The results of the current study indicate that these 3300 properties are likely to have soil lead concentrations elevated above the recommended soil guideline value of 210mg kg^{-1}. Another 4150 standalone residential properties in Palmerston North City were built between 1940 and 1960 are likely to have some elevated soil lead concentrations, although it is not expected that this would exceed the soil guideline value (Ministry for the Environment, 2011a). Nationally, there is an estimated 227,000 residential properties built prior to 1940 that are likely to exhibit similar levels of lead-based paint contamination exceeding the lead SGV as that observed in the current study (Page & Fung, 2008; Statistics New Zealand, 2013). Additionally, there is an estimated national stock of 284,000 residential properties built between 1940 and 1960 that may show some degree of elevated soil lead concentrations, although again such properties will not necessarily exceed the current regulatory SGV of 210mg kg^{-1} based on the findings presented here (Page & Fung, 2008; Statistics New Zealand, 2013). Of these 511,000 properties, approximately 411,000 (80%) were of weatherboard construction according the New Zealand Yearbook (1960). It is likely that these residential properties will exhibit elevated concentrations of soil lead due to historical lead-based paint use with the 411,000 weatherboard properties likely to exhibit significantly elevated soil lead concentrations due to painting during construction. This presents a significant issue for New Zealand land owners and regulators in managing risk to human and environmental health.

6.1.1.1 Exposure Pathways

The actual risk to human health and sensitive receptors such as children needs to be adequately quantified to ensure that exposure risk is minimised without creating undue burden on home owners to remediate residential properties. Exposure requires a complete pathway between source and receptor. Sample location, lead mobility, exposure scenarios and receptor sensitivity must also be accounted for when assessing exposure risk. The results of this study have demonstrated that the highest concentrations of lead in sampled properties are closest to painted structures and within the top 0-10cm of soil. On most sample properties these areas were ornamental gardens, or grassed lawn. Grassed lawn and gardens with groundcover are not anticipated to present a risk to receptors except during deliberate soil disturbance activities such as gardening (Ministry of Health, 2012; Paltseva et al, 2018; Public Health England, 2019). In these areas it is not likely that soil with elevated concentrations would be tracked inside or come into contact with receptors other than when deliberate soil disturbance activities occur (Laidlaw et al, 2017). Ingestion of contaminated soils and dust is considered the dominant exposure pathway for lead to humans (Kandic et al, 2019; Ministry for the Environment, 2016; Ministry of Health, 2012). The exposure risk from soil lead concentrations observed during the current study can be inferred using current regulatory limits and results from previous studies investigating the bioavailability of lead in soils. All of the properties investigated as part of the current study had a land-use classification of standard residential (10%

produce) which has a SGV of 210mg kg^{-1}. The average soil lead concentrations in weatherboard properties first constructed before 1945 were all in exceedance of this SGV with individual samples an order of magnitude higher. The actual exposure risk may be less than it first appears as the bioavailability of lead has been shown to vary between 10% and 90% depending on site specific factors (Codling, 2013; Ministry for the Environment, 2016; Yan et al, 2015). The current soil guideline value for lead is based on an assumed bioavailability of 100% when in many cases this has been shown to be too conservative (Codling, 2013; Golder Associates, 2012; Ministry for the Environment, 2016; Wijayawardena et al, 2015). Wijayawardena et al (2015) showed that the relative bioavailability of lead varied between 30% and 83% for lead contaminated soils from various industrial and horticultural sources. For properties where soil lead was derived from lead-based paint, Codling (2013) showed a bioaccessibility of between 30-50%, indicating that lead-based paint may be less bioavailable than industrial sources. Other studies have agreed with this finding (Clark & Knudsen, 2014; Clarke et al, 2015; McClintock, 2015) showing that approximately 30-50% of residential soil lead was associated with the exchangeable and carbonate fractions which are the most bioavailable. The reducible fractions associated with lead-chromates and lead-oxides as paint additives are less bioavailable and made up approximately 40% of the total soil lead in previous studies (Clark & Knudsen, 2014). If we adopted the more conservative bioaccessibility of lead found by Codling (2013) of 50%, this would allow for soils with concentrations of lead up to 420mg kg^{-1} to remain on site, reducing the need for costly remediation which may not be justified by risk. Incorporating lead bioavailability assessment into human health risk assessments allows for a more accurate determination of exposure risk that takes into account site specific information (Ministry for the Environment, 2016). Use of *in vitro* methods of assessing bioaccessibility have been sufficiently correlated to bioavailability that these have been approved for assessing risk in some regulatory systems such as the USA (United States Environmental Protection Agency, 2012). Before any mitigation or remediation measures are undertaken on impacted properties, it is imperative that the risk is adequately quantified to avoid unnecessary costs. A discussion of mitigation and remedial options is presented in Section 6.2.

6.1.1.2 Health Effects

In Palmerston North City there are approximately 12,000 people under the age of 20 occupying standalone homes first constructed before 1980 (Statistics New Zealand, 2013). The findings of the current research indicate that these properties will have soil lead concentrations elevated above background levels, and in homes first constructed prior to 1945, above the SGV (Ministry for the Environment, 2011a). This cohort represents 15% of the total population of Palmerston North City and is considered the most vulnerable to lead exposure (Nigg et al, 2008). The soil lead concentrations and estimated volume of properties with lead contamination shown by the current study indicate that there should be more cases of lead exposure than are currently being reported. There is likely to be some exposure mitigating factors present, given that there are on average only 143 notifiable blood lead level exceedances annually in New Zealand (Ministry of Health, 2012). Possible factors could include occupancy tenure of contaminated properties, existing soft cover, misdiagnosis of lead exposure symptoms, and behaviours such as diet. A review by Kordas (2017) of nutritional advice for persons with elevated blood lead levels reported that increased blood lead levels have been correlated with poor nutrition. In particular, iron and calcium deficiencies are correlated with increased blood lead concentrations in children, as these essential nutrients are absorbed in the body by similar biological functions. It is possible that misdiagnosis of the symptoms of lead exposure may also result in underreporting of notifiable cases (Ministry of Health, 2012). The current consultation to halve the notifiable blood lead level being undertaken by the Ministry of Health (2019) is likely to result in more cases and provide the impetus to continue reducing lead exposure in New Zealand. The management of human exposure to lead in New Zealand is by the Ministry of Health who advocate, inform and treat sources, exposure pathways and symptoms of lead exposure (Ministry of Health, 2012). This is similar to the United States with the Federal Action Plan to reduce childhood blood lead levels nationally (United States Environmental Protection Agency, 2018). The United States approach addresses the issue of lead-based paint contamination in residential soils with proactive messaging and community engagement (United States Environmental Protection Agency, 2018). Further community engagement to increase awareness and mitigation strategies could be an effective way of limiting exposure and managing these sites in New Zealand (Section 6.2).

6.1.1.3 Socio-economic implications

Properties in poorer condition were found to have elevated soil lead concentrations due to flaking lead-based paint. Poor housing condition is correlated with lower incomes

(McClintock, 2015) indicating that the soil contamination issue is more likely to impact those that can least afford to manage it. Lower socioeconomic groups are more likely to undertake work themselves which may lead to elevated soil lead concentrations McClintock, 2015). A summary of studies investigating diet and blood lead levels by Kordas (2017) showed that deficiencies in iron and calcium as well as irregular eating patterns are correlated with higher BLL, especially in children. Prevalence of poor nutrition and irregular eating patterns are more prevalent in lower socioeconomic groups (Kordas, 2017). Therefore, lower socioeconomic groups are likely to experience both higher soil lead concentrations and greater susceptibility to lead exposure.

6.1.2 Environmental Health Implications

In New Zealand, lead has been shown to cause reproductive inhibition in invertebrates at concentrations as low as 35mg kg^{-1} and cause toxicity to microbes at concentrations as low as 49mg kg^{-1} (Landcare Research, 2016). However, in New Zealand the ecological soil guideline value is set at 1276 mg kg^{-1} for weathered lead for the protection of 95% of species (Landcare Research, 2016). The impact on urban infaunal species found in lead impacted residential soils is not well studied, likely due to residential and urban soils being perceived as of lower ecological importance when compared to agricultural soils or areas of high ecological value. Previous studies have investigated the uptake of heavy metals including lead in plants grown in contaminated soils as a potential pathway to humans (Paltseva et al, 2018). However, potential impacts on growth and reproduction have not been widely studied. There is potential for elevated soil lead concentrations to negatively impact plants grown in lead-contaminated soil although this is not considered to be of critical importance when addressing the problem of lead in residential soils. Bioavailability studies using *in vivo* techniques on rats and swine indicate that elevated blood lead concentrations cause negative health effects in exposed animals (Chaney et al, 1989). The current study did not investigate the impact of residential lead on biota within the residential soil environment, however observations were recorded during sampling that revealed no obvious variation between the ecological health of residential properties that were impacted by lead and those that were not. Earthworms were noted in soil samples with lead concentrations exceeding 2000mg kg^{-1} and did not appear to vary in abundance from sample to sample. The exception was that organic garden soils were noted to have more earthworms than lawns although this is most likely related to soil type and presence of food sources. From the current study, the predominant concern with elevated lead in residential soils is human exposure. Further studies into ecological impacts would provide better characterisation of the ecological impact.

6.2 Potential Solutions

Exposure to contaminated soil through the common pathways discussed in this chapter can be minimised through site management or remediation techniques (Golder Associates, 2012; Ministry for the Environment, 2016; Rouillon et al, 2017). Current practice for remediation of larger sites where there are multiple dwellings present often involves removal of the upper 30cm of soil around the property footprint and disposal at landfills (Golder Associates, 2012). However, this may not be a suitable option given the volumes of potentially contaminated soil. Mitigation strategies such as soil amendment, imported cover or behavioural change may provide a more effective and inexpensive method of addressing elevated soil lead concentrations. The removal of contaminated soil from more than 500,000 residential properties across New Zealand is not considered a realistic option with national landfill capacity already facing pressure from increased disposal volumes (Ministry for the Environment, 2016). The cost of site assessment, professional advice and offsite disposal would also be a financial burden to homeowners. The high cost of landfill disposal and limited national landfill capacity makes this option practically and financially unachievable (Ministry for the Environment, 2016). Partial soil removal from ‘hotspot’ locations such as around the immediate curtilage of the house or in sensitive locations such as play areas, vegetable gardens and entrances where exposure risk is higher could be effective mitigation strategies (Laidlaw et al, 2018; Rouillon et al, 2017). This would reduce the cost burden of soil disposal while significantly minimising the exposure risk. Other mitigation strategies could include the use of soft or hard cover to break the exposure pathway (Ministry of Health, 2012). Soft cover options such as importing clean fill onto site, planting groundcover vegetation or mulching/weedmat may provide a low cost option to reducing exposure risk on impacted properties (Public Health England, 2019; Ministry of Health, 2012). Soft cover options reduce the exposure to contaminated soil but require ongoing maintenance and behavioural change as such techniques do not permanently remove the risk. Hard cover options such as paving or concreting has a similar effect in breaking the exposure pathway but requires less maintenance than soft cover options.

Unlike common pollutants such as hydrocarbons, lead does not undergo microbial or chemical decay in the soil environment (Mahar et al, 2015). The use of soil amendments that can bind and immobilise lead, may reduce its availability and therefore risk to human health (Freeman, 2012; Mahar et al, 2015). Commonly available phosphorus compounds, lime and animal manure have been shown to reduce the mobility of lead within soil, decreasing its bioavailability (Mahar et al, 2015). Soil amendments have been shown to work on a neighbourhood scale in a project undertaken by the United States Environmental Protection Agency (Freeman, 2012). Locally available fish bone waste which is naturally high in phosphorus was worked into soils of a residential neighbourhood with historical lead contamination (Freeman, 2012). The phosphorus in the fish bones bound to the lead, and follow up sampling showed significantly reduced bioavailability decreasing the exposure rate for residents without altering the overall soil lead concentration (Freeman, 2012). Commonly available composts are often high in phosphates and can produce a similar effect, reducing lead bioavailability (Freeman, 2012).

Public awareness and behavioural change should also be part of a combined solution to soil lead contamination at residential properties. Soft and hard cover options require ongoing maintenance that would be the responsibility of the occupier or owner and would need to be communicated through any change of ownership to ensure that risk mitigation measures are maintained. Raising awareness of the risk and possible mitigation strategies would aid homeowners in making appropriate decisions about managing any potential risk on their property. Lead-based paint hazards and contaminated residential soil is a global problem and regulators such as in the UK (Public Health England, 2019) and USA (United States Environmental Protection Agency, 2019b) have increased information and awareness campaigns in recent years. Citizen science initiatives such as the Vegesafe program in Australia raise awareness and provide confidential, affordable and accessible soil testing for property owners (Kandic et al, 2019; Rouillon et al, 2017). Similar community engagement initiatives in New Zealand could be used at fairs to offer free blood testing and advice as well as raising awareness of potential issues (United States Environmental Protection Agency, 2018). The current regulatory regime for managing contaminated land in New Zealand does not have adequate methods or triggers for investigating and managing contaminated soils on residential properties where no historical industrial or potentially polluting activity has taken place. Potential regulatory mechanisms through Worksafe and the Ministry of Health could be used to require inspections in homes or areas where children could be exposed such as schools and day care facilities similar to in the United States (United States Environmental Protection Agency, 2018). Any regulation regarding the management of properties impacted by historical use of lead-based paint will need to provide sufficient information and options for management so that undue financial burden is not placed on homeowners. With an estimated 511,000 lead impacted residential properties nationally, there may also be an economic impact in the form of reduced land values as public awareness increases. Action needs to be taken to ensure that the risk from lead-based paint impacted sites is communicated to sensitive receptors such as families occupying affected properties.

6.3 Recommendations for Further Work

The research presented in the current study better quantifies the scale of lead-based paint contamination within New Zealand. This study has demonstrated a clear pattern of soil lead distribution both laterally and vertically across residential properties and has better defined the property characteristics indicative of lead-based paint contamination. However, further work is required to effectively evaluate the risk that this contamination poses to occupiers, in particular the most vulnerable in our population. Further research into the exposure risk from lead-based paint contamination is necessary to inform appropriate management techniques to reduce or remove exposure pathways. This could include investigations into particle size analysis, soil pH, lead fractionation and the effects of organic carbon on the bioavailability of lead from lead-based paint. Recent bioavailability work has focused on lead contamination from horticultural and agricultural sources (Golder Associates, 2012) which may have different bioavailability compared to lead-based paint. Further isotopic analysis of residential soil lead would help to determine the contribution of historical lead additives in petrol to total soil lead concentrations. Research into the links between soil lead concentrations, house dust lead concentrations and blood lead levels would provide a comprehensive assessment of exposure risk and investigation of actual impacts. However, there are significant ethical implications and study design would have to account for individual behaviour.

6.4 Conclusions

This study provides a robust and comprehensive investigation into lead-based paint contamination of residential soils in Palmerston North City, New Zealand. Soil lead concentrations were found to increase with house age with houses constructed prior to 1945 having significantly higher soil lead concentrations than younger properties. Soil lead concentrations decreased with distance from the house and decreased with depth indicating that lead-based paint is the dominant contributor to lead in residential soils. Construction type was shown to have a significant influence on soil lead concentrations with weatherboard homes exhibiting significantly higher concentrations than all other construction types. There was no strong evidence of diffuse contribution to soil lead concentrations from historical use of leaded petrol at any property sampled.

The results of this study define the lateral and vertical distribution pattern of lead-based paint contamination across residential properties in a regional New Zealand city. Based on the findings presented here, approximately 227,000 homes in New Zealand built prior to 1940 may have mean soil lead concentrations that exceed the current soil guideline value for lead in residential scenarios (10% produce) of 210mg kg^{-1} (Ministry for the Environment, 2011a; Page & Fung, 2008). An additional 284,000 properties built between 1940 and 1960 are estimated to have elevated soil lead levels as a result of historical lead-based paint use. The results of this study suggest that there will be minimal lead contamination of soils for houses built between 1960 and 1980 (541,000).

The influence of soil parameters like organic carbon, pH and particle grain size distribution will help in assessing the risk of exposure. Bioavailability research is needed to further investigate the exposure risk and health implications associated with elevated soil lead concentrations from a lead-based paint source. Further research is needed to investigate the relationship between soil lead concentrations and blood lead levels in New Zealand.

The findings of this study present a challenge to regulators, contaminated land professionals and property owners investigating, managing and remediating lead impacted residential soils. The current regulatory framework does not allow for consistent identification and management of residential properties impacted by lead-based paint contamination. Lead-based paint contamination is likely to cover large tracts of New Zealand's urban soils and effective and reliable policy for risk assessment and management of these soils is necessary to reduce the risk to the most vulnerable in our population.

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Appendix 1 – Participant information sheet

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

School of Agriculture and Environment
Te Kura Mātauranga mō Ahuwhenua me Te Taiao

AgHort B,
University Avenue,
Palmerston North 4474

Investigation of Lead Based Paint Contamination in Residential Soils within Urban Centres of Manawatu-Wanganui

INFORMATION SHEET

What is this all about?
My name is Jack Blunden and I am undertaking postgraduate student research project as part of a Master of Earth Science Degree at Massey University. The project is being supervised by Professor Chris Anderson of the School of Agriculture and Environment at Massey University in Palmerston North. The project is looking at concentrations of trace elements such as lead in residential soils.

What is the purpose of this research?
The purpose of this research is to identify if there is a link between concentrations of lead in the soils of residential properties and the historical use of lead paint. This topic has come about because of a growing interest in the quality of our environment and impacts on this from historical activities. This project will also be looking at the concentration patterns around the property and between properties of different ages or construction type.

I would greatly appreciate your agreement to take part in this study and we intend to use the findings to improve current knowledge on the impacts of historical lead paint use.

How were you chosen for this invitation?
We would like to invite you to participate because you are listed on the Massey University contact list and live in the Manawatū -Whanganui region where we hope to undertake all of our soil sampling. We are hoping to reach as many potential participants as possible to improve the quality of the research.

If you would like to participate, how do you volunteer?
If you would like to participate that is great news! Please email 19025867@massey.ac.nz. We are hoping to begin sampling in May, June and July 2019 so please express your interest as soon as possible.

We really appreciate your willingness to be part of this research. We will be selecting as many properties as possible (up to 100) so that we have a large dataset but we have a few key criteria that you must meet. You must;

- Be an owner occupier and not leasing or renting out the property.
- Have a property constructed prior to 1980

Participation in this research will not require any involvement from you beyond providing access to the garden/lawn surrounding you property for me to take soil samples. We are not a funded project so cannot provide compensation for your participation however we will share the soils sample results with you if requested. If you are selected to participate I will be in touch with to find out more about your property such as construction type, age, urban/rural and to agree dates for soil sampling.

If you participate, what will you need to do?
All you need to do is provide access to the external areas of the property for the researcher to undertake soil sampling. This should take no longer than 1-2 hours and will be a single visit. Approximately 4-15 soil samples will be taken from soil around the edges of the house using a soil sampling scoop. This will only remove about 200grams of soil and the hole will be backfilled with surrounding soil so that there are no noticeable holes.

The soil samples will be taken to the University Laboratory where they will be analysed. If you want to find out the results from your property we will share these with you.

Will this affect me?
This research will investigate the current soil quality and will not alter this in any way following sampling.

If you wish to receive your results and find that there is lead in your soil, visit the Ministry of Heath website for further guidance regarding safe levels and what to do if you receive a high reading- https://www.health.govt.nz/your-health/healthy-living/environmental-health/hazardous-substances/soil-contaminants-and-health.

If you participate, how will your data be managed and stored?

Raw data will be stored securely in password protected electronic files accessible only by the research team. Raw data and soil samples will be destroyed following completion of the project within two years

You and/or your property details will not be identifiable in the final report- soil analysis results will be made available to the homeowner only if requested. At any time you can contact me to request information regarding your property and can withdraw from the study if you change your mind at any point.

If you participate, what are your rights?
You are under no obligation to accept this invitation. If you decide to participate, you have the right to:

- decline to answer any particular question;
- withdraw from the study (specify timeframe);
- ask any questions about the study at any time during participation;
- provide information on the understanding that your name will not be used unless you give permission to the researcher;
- be given access to a summary of the project findings when it is concluded.

So who is involved in this project?
Jack Blunden (Thesis student)
M: [redacted]
E: [redacted]

Professor Chris Anderson (Thesis supervisor)
E: c.w.n.anderson@massey.ac.nz

If you have any further questions about participating in this research project please don't hesitate to contact me and I'll endeavor to answer all of your questions.

Kind Regards,

Jack Blunden

Massey University Masters Student
Student ID [redacted]

"This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named above are responsible for the ethical conduct of this research. If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Prof Craig Johnson, Director, Research Ethics, telephone 06 356 9099 x 85271, email humanethics@massey.ac.nz".

Appendix 2 – Participant consent declaration

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

School of Agriculture and Environment
Te Kura Mātauranga mō Ahuwhenua me Te Taiao

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PARTICIPANT CONSENT FORM

I have read, or have had read to me in my first language, and I understand the Information Sheet attached as Appendix I. I have had the details of the study explained to me, any questions I had have been answered to my satisfaction, and I understand that I may ask further questions at any time. I have been given sufficient time to consider whether to participate in this study and I understand participation is voluntary and that I may withdraw from the study at any time. I understand that all the information I provide will be kept confidential to the extent permitted by law, and the names, addresses of all participants in the study will be kept confidential by the researcher.

1. I **agree/do not agree** to have photographs of the sampling location placed in an official archive
2. I **wish/do not wish** to have the soil sample analysis results supplied to me.
3. I **wish/do not wish** to have my data placed in an official archive.
4. I agree to participate in this study under the conditions set out in the Information Sheet.

Declaration by Participant:

I ___________ [print full name]___________ hereby consent to take part in this study.

Participant Consent Form 28/07/2019 | Page 1 of 2

Signature: ______________________ Date: _______________